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APPLICATION OF DIGITAL SIMULATION AND MATHEMATICAL OPTIMIZATION TECHNIQUE IN RIVER POLLUTION CONTROL

BY

© C. L. NARASIMHAN

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE

DEPARTMENT OF COMPUTING SCIENCE

EDMONTON, ALBERTA

CANADA, FALL 1979

THE UNIVERSITY OF ALBERTA

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled "APPLICATION OF DIGITAL SIMULATION AND MATHEMATICAL OPTIMIZATION TECHNIQUE IN RIVER POLLUTION CONTROL" submitted by CHALUVE LAKSHMI NARASIMHAN in partial fulfilment of the requirements for the degree of Master of Science in Computing Science.

Supervisor

Date Sept. 10, 1979.

To my parents

ABSTRACT

A simulation model has been developed to provide a broad-based capability for analyzing water pollution in a complex river system. In principle, one powerful management tool is systems analysis, wherein mathematical optimizing techniques are employed to effect rational tradeoffs between several competing river pollution control designs. This objective has been accomplished by integrated utilization of computer based simulation and dynamic programming optimization technique.

A discrete, deterministic, dynamic programming algorithm developed in this work is shown to be of much use in the areas of water pollution control and management. Given a set of conditions, the optimization model determines several combinations of the quantity of pollutents and the the quantity of artificial aeration required to meet a pre-specified water quality standards. The objective function is the minimization of the sum of the squares of the aeration costs and the costs incurred by damaging the quality of river water or unnecessarily improving the system. The original constrained allocation problem is simplified by converting it to an unconstrained one via the use of Lagrange multiplier.

The simulation model, including the dynamic programming optimization model was applied to the North Saskatchewan River. A typical optimal aeration capacity allocation policy and its corresponding water quality profile for the North Saskatchewan river is presented. The relationship between the total available aeration capacity and Lagrange multiplier is also developed treating weighting factor as parameters.

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CHAPTER ONE

INTRODUCTION

1.1 GENERAL DESCRIPTION

Since the turn of the century, research that has been directed towards the field of environmental engineering has resulted in an extensive array of technology that can be employed to minimize the impact of man on his surrounding environment. Only fairly recently, however, have certain researchers directed their efforts toward a mathematical description of a variety of systems both natural and man-made, that are significant to environmental engineering. Dynamic and steady-state mathematical models which have resulted from the various investigations have been developed to the extent that they can be employed to delineate solutions to real-world questions. Armed with a descriptive and structural model, an environmental engineer can evaluate design and operational alternatives as well as control strategies through a series of computer simulations, thus placing him in a preferred position in decision-making. While models in and of themselves are not a panacea, within certain bounds and limitations, system simulations can provide valuable assistance to the environmental engineer.

Although models which have evolved during the past

decades have been extensively employed for description and simulation of laboratory research results, they have only occasionally been employed for the design, operation, and control of man-made systems or for the planning and management of natural systems. There is no doubt that the pollution control efforts which are now under way have already borne some fruit. Due to the pronouncements of the more lurid popular articles during the last 2 or 3 decades, the condition of some of the most heavily used streams have improved markedly. Nevertheless, serious problems of water quality still confronts the world. Their solution will lie not only in the field of engineering but also require the very best efforts of economists and computer technologists.

The decisions of a control engineer can be no sounder than the basic information and insights concerning water pollution. For a decision maker, therefore, ready access to the current knowledge in many areas involved in pollution control decision is a matter of extreme importance.

1.2 Systems Analysis and Pollution Control

The electronic computer, one of the modern technological developments, has profoundly changed the scientific world. Its ability to handle complicated information has dramatically expanded environmental engineering boundaries.

The combined pressure of growing population, rapidly expanding industries, and increased demand on agricultural lands are creating serious threats to the quality of the environment. For years, wastes other than those directly affecting public health caused little concern. But as the way of life became more complex, the pressure for pure water and clear air touched practically all segments of economy. New and increasingly stronger legislation has been enacted in an attempt to protect water and air resources.

Effective pollution control requires the coexistence of at least three factors:

1. high level of knowledge and dedication on the part of environmental engineers and researchers,

2. a sincere Government commitment to clean waters, manifested in a workable regulatory scheme.

3. public understanding of the nature of the pollution problem and support for the control efforts.

However, the discussion of the factors mentioned above are beyond the scope of this work. It is hoped that the materials contained in this work would be both informative and useful to water pollution authorities. However, this work is a mere scratch on the surface of the body of

knowledge that will be required to cope adequately with the present and emerging problems of water pollution control. It is hoped that the optimization by dynamic programming approach via the lagrange multiplier idea will stimulate others to undertake research in this most vital and challenging field - river pollution control.

1.3 Literature Review.

During the past two decades, a significant effort of research has been devoted to the study of pollution control strategies and the analysis of waste water treatment facilities. As a result, many different analytical methodologies have been developed using linear and nonlinear programming techniques. However, in establishing the managerial goals for a water quality management system, the deterministic nature of quality standards has played profound roles in modeling processes.

The methods of operations research, systems analysis and modern mathematical analysis have been applied with increasing intensity in the fast few years. In many cases, the methods admit direct application in water resources management. Although the number of people in water resources field having an ability in system field is relatively small, these few have made substantial progress.

The first major effort to apply operations research and systems analysis in water resources studies was by the Harvard Water Program, which was started in 1956 and culminated in 1962 with the publication of a text book-like report of the research objectives, concepts, methods and techniques. Fiering (1961, 1964, 1967), Hufschmidt and Fiering (1966), Thomas (1963) and Matalas (1967) are among the many workers of the group. The subjects are all concerned with operation research, systems and simulation techniques in the solution of water resources design problems.

Another sprinkling of papers came from Northwestern University where Charnes influenced the use of digital simulation which includes the possibility of using effluent storage and low-flow augmentation as control variable. Lynn, Logan and Charnes (1962); Logan (1962); Lynn (1964); Deininger (1965) and Heaney (1968) are examples of work from this source. The Lynn influence has since spread to Cornell University where such work as Liebman and Lynn (1966), Loucks and Lynn (1966), and Loucks, ReVelle and Lynn (1967) have resulted. The objective of all their simulation study was to develop a model to represent a sewage treatment system in which various combinations of 'treatment' elements and operating disciplines were used to measure the effectiveness of the system for given configurations.

In U. S. Public Health Service study of the Delaware River Basin, extensive use of these methods of analysis was reported by Thomann (1967). Grantham and Schaake (1971) have presented the use of simulation as a tool to study the surface water hydrology of a stream. Kolo and Haimes (1973) have extensively used simulation for planning and expansion of regional water resource systems for Ohio river.

1.4 Source of Pollution

Pollution of streams results from man's activities at home, in factories, and in form. At home water is used for many purpose most of which involve adding solid content to water. The detergent problem resulting from domestic water use creates many difficulties. Unfortunately, it is biologically nondegradable and relatively unaffected by conventional waste treatment methods. In wastes it produces foam in rivers and interferes with normal water and waste treatment.

Significant pollution also results from industries such as chemical, meat packing, dairy, canning and tanning. All industries use large amounts of water for processing products. The used water contains large quantities of decomposable organic matters such as milk waste, offal from animals, decayed fruits and vegetables. In general, the polluting power of such industrial wastes will exceed the polluting power of wastes resulting from a strictly domestic population by ten or even twenty times.

Technology is ever advancing and new products are developed and old ones abandoned before the pollution significance of some of them can even be determined. Today seventy five percent of drug store prescriptions involve drugs unknown five years ago. In many chemical industries,

the majority of sales involves products unknown two or three years ago. Thus, the source of wastes and their complexity can be expected to increase directly with the growth of industry, particularly the chemical industry.

1.5 Effect of Pollution.

For years, health educators have preached against water pollution, citing pollution as a major threat to public health, esthetics, and economic use of water resources. The measure, not only of the "cleanness" of a river, but also of the capacity of a river to absorb pollutional loads placed upon it, is the amount of dissolved oxygen (D.O) which the river contains. The absence of dissolved oxygen, combined with industrial and municipal pollution produces a septic condition which not only prohibits, the recreational use of water, municipal water supply, the presence of fish life but also creates a taste and odor problem for downstream users of river.

Pollution can also significantly increase the costs involved in subsequent uses made of polluted water. It can increase the cost of water treatment for municipal and industrial use.

But how do you go about evaluating how much pollution is too much? How far back should we roll pollution? How do

we evaluate the reduction of water use value against the cost of eliminating the pollution? Certainly we do not expect to return all our streams to 'wild stream' status. This whole area requires much coordinated interdisciplinary study so that decisions can be based on facts, not on desires only.

1.6 Water Quality Criteria

In view of the large number and variety of uses to which water is put, a number of different standards of stream quality have been developed. The water pollution control agencies serve to outline in detail exactly what constitutes pollution in each case. In establishing a qualitative standard for receiving body of water, the water pollution control agency must consider the current and future water needs of the entire region. The river water may be used for a source of water supply, for recreation, and for receiving wastes. The standard of permissible pollution, thereafter, must be established on a basis that will bring to the public which inhabits the river, the greatest benefit for the least cost.

The most important indices representing stream water quality are biochemical oxygen demand (BOD) and dissolved oxygen (DO) content. The BOD concentration denotes the amount of oxygen required for complete biochemical decomposition of the organic wastes contained in water. Hence, the BOD decomposition indirectly represents the total amount of organic waste (pollutant) in water. The DO concentration represents the water oxygen content. For a natural stream, i.e., a stream unpolluted by waste discharge, the DO concentration is at a level of about 80 to

90 percent saturation (7 to 14 mg/l[1] depending on stream conditions) and the BOD concentration is below 10 mg/l. Under normal conditions, a DO concentration of 5 mg/l is sufficient for maintaining a normal acquatic life (Krenkel and Parker 1969) and to preserve a satisfactory water quality for multipurpose use. When the level of DO drops significantly below the standard due to a heavy pollutant load discharged somewhere upstream, artificial aeration augmentation can be uesd to raise the level of DO to a specified level.

1.7 Preview

In Chapter 2, the motivation for the application of digital computer as a tool in river pollution control is presented in detail and a few of the well known computer languages for simulation are reviewed.

In Chapter 3, the details of the proposed method (Dynamic Programming Technique) is presented with a typical example problem.

In Chapter 4, a mathematical model of the system and a discretized dynamic programming algorithem is formulated for finding the optimal allocation policy. The original

---

[1] Defined in Appendix-C.

constrained allocation problem is simplified by converting it to an unconstrained one via the use of Lagrange multiplier.

In Chapter 5, details of application of the model to North Saskatchewan river is explained along with the analysis of the result.

Chapter 6, includes the summary of the results and some proposals for further research in this area.

CHAPTER TWO

ROLE OF COMPUTER IN POLLUTION CONTROL

2.1 Introduction

The use of simulation as a tool for planning, construction, and operation of complex systems has increased materially in the past decade, principally due to the advent of digital computers. Their ability to handle complicated information have dramatically expanded engineering boundaries. In so doing, it has simultaneously created numerous opportunities for the application of mathematical ideas and methods to the solution of traditional scientific problems and made possible the exploration of research areas in engineering and science either previously unattainable or undreamt of.

In recent years, there is an increasing interest in the application of computers to water pollution control. The successful implementation of automated process control in petroleum, chemical, steel, and other industries has strongly stimulated the investigation of a similar control in river pollution. Environment administrative personnel have begun to realize that computer simulation of river system would give good answer to:

(a) achieving the increasingly stringent requirements mandated by regulatory agencies;

(b) combatting the rising cost of power and qualified labor;

(c) optimizing intgrated river pollution control systems;

(d) generating the myriad information for operations, management, and environmental regulatory agencies.

Computer applications to the monitoring and reporting of plant functions are becoming common and are receiving widespread acceptance as a standard practice. This fact is so fundamental to the whole approach that both industries and universities are, in fact, revising classical engineering practices to accommodate the computer. This capability can be employed most effectively in river pollution control. In simulation, the computer provides a basis for finding the most economical design as well as several feasible alternatives.

2.2 Necessity of Computer Simulation

Any river pollution surveillance program has to handle a great deal of data. Efficient operation demands that the data be well organized and be available for use when it is required. For this a good information storage and retrievel system of a quality and magnitude, which only a digital computer can handle is essential. An example of what such a

system can handle is the management of fifty years of data for nearly twenty four waste disposal stations (about a million values) situated on the banks of the North Saskatchewan River near Edmonton, Alberta. So the role of the digital computer is important; apart from the fact that it makes mathematical computations with unbelievable speed and accuracy, it is able to store and recall mathematical formulas and data in copious quantities. The whole problem, mathematical relationships and data, must be clearly and explicitly defined. The computer is able to simulate in fast time, generating many years of operational data in a few minutes.

In economic terms, the computer application often achieves a very low cost per calculation, while requiring a relatively high initial cost. It should be recognized, however, that once a computer program has been developed, the initial cost for reuse in subsequent projects is usually negligible or marginal. Cost per calculation is not the only factor which should be considered when evaluating the advantages and disadvantages of computer usage. The accuracy of calculation and the total amount of information that can be generated must also be considered. The computer can often utilize a more exact set of equations and it can process information approximately one million times faster than a human being. In addition, once the program has been debugged, the rate of mistakes by computer is negligible.

The indispensability of the computer in simulation and optimization of river pollution control model will be quite obvious from chapters three, four and five of this thesis.

The information obtained from simulation becomes a comprehensive source of operational data. This information can fulfil management's needs for investigating operational trends, studying operation costs, and developing data correlations for pollution control. Once in operation, the computer reporting system comprises the data base for further improvement of the model. Such operational data are vital in evolving models and validating them. Further, the computer reduces the time required for technical and clerical record keeping, minimizing human errors, and enhances data accessibility. The data available in the memory of the computer can be statistically analyzed and furnished to engineers for design purpose. Without computer assistance, preparation and collection of such information may become too tedious.

The value of simulation lies in its flexibility. A simulation system can be operated under all variations of normal and extreme conditions and can be checked out and evaluated entirely by the computer. Many questions can be asked during simulation and the validity of the answers is an indication of how well the model represents the true system or prototype.

2.3 Methods of Simulation in Pollution Control

There are two general types of computers used in simulation namely:
Analog (continuous-variable) and Digital (discrete-variable) computers, and both types are employed in simulation studies. A simulation technique is classified as analog or digital, depending on the way the problem is formulated and the type of computer needed for the formulation and solution.

2.3.1 Analog Simulation.

An analog computer is one in which computation is performed by varying the state of some physical elements in which the variables are continuous. When analog simulation is employed, all parts of the system must be simulated simultaneously. The parallel nature of analog simulation therefore makes it closer to system behaviour than does digital simulation.

Each component or function of the analog simulation system must be simulated by one or more components in the computer. This nature of analog simulation always requires the addition of more computer equipment as the system being simulated becomes more and more complex. For small systems

this requirment is not serious, but for the study of large systems the addition of more simulator elements can become expensive. Moreover, in many cases further additions of simulator elements may not be feasible because there is a practical limit to the number of simulator elements that will work together satisfactorily.

Furthermore, the accuracy of the analog computer is limited to the accuracy of the physical components involved. Thus, the use of analog simulation in river pollution studies becomes attractive when a special part of a general system is to be scrutinized, and analog technique becomes less attractive as the problem under study becomes more and more generalized.

2.3.2 Digital Simulation.

Digital simulation is characterized by the use of a digital computer. Whereas the analog computer must handle all elements of the simulation system simultaneously (in parallel), the digital computer handles elements of the simulation system one after another (in series). Hence, an increase in the system complexity results in an increase in the time required for computation. Although accuracy may not necessarily be an important factor in the simulation, it is possible in digital simulation to reach any degree of accuracy desired by carrying out more computations.

Moreover, explosive development of ever faster and less costly digital computers, coupled with better software and integration routines, seem to indicate the demise of analog/hybrid simulation, except for some interface equipment needed in partial system tests (e,g., with autopilot components, man-in-the-loop). As a case in point, training-type flight simulators have been all-digital for years. As a rule of thumb, a 1973 16-bit minicomputer can comfortably simulate a three dimensional aircraft engine equations three times faster than real time (G. A. Korn, 1973) if we use fixed-point computation and omit fast sub-system such as hydraulic servos.

2.4 Simulation with FORTRAN

In discrete-event simulation the language used must enable the system designer to represent a complex system conveniently and implement comfortably. The representations could involve such requirements as solving of equations, preserving interrelations, representing decision logics and physical characteristics of the system. The languages employed vary from Assembler languages through the general purpose programming languages (FORTRAN, PL/1, ALGOL) to the general purpose Simulation languages (GPSS, SIMSCRIPT, DYNAMO). In RIPSIM (RIver Pollution SImulation Model), the general purpose programming language FORTRAN IV was used as the tool over the available general purpose simulatiom

languages, notably GPSS, for the following reasons:

(a) GPSS/360 is available only on larger machines so that the use of such a language would limit the scope of the model and hence its use as a tool for the environmental engineers.

(b) The speed of execution in GPSS tends to decrease with the growth of model size and complexity; and as a tool, it is important that execution be as fast as possible to make the use of the model economical.

(c) It is easier to expand or decrease the size of the model through redimensioning of the appropriate FORTRAN arrays than it would be for a novice programmer to use the REALLOCATE feature in GPSS to expand a model programmed in GPSS.

According to Reitman(1974) the general requirements of a language in the area of simulation may be reduced to four basic characteristics as follows:

1. Short-term results;
2. Ability of system to represent the real world;
3. Long-term results;
4. Effort required.

1. Short-term results. The system designer must have a

good programming background in the language before he can use it for simulation. But FORTRAN, being one of the most common languages gives less difficulty as far as background in programming is concerned.

2. Ability of system to represent real world. Almost any real-world condition could be represented in FORTRAN; the effort goes up, however with complexity in a nonlinear relationship.

   (a) Logical situations in the model can be represented without difficulty.

   (b) Mathematical capability of the language is excellent. There are numerous special-purpose techniques for data smoothing, and other forms of data manipulations which are both available and accessible for simulation.

   (c) Maximum model size is completely under the control of the programmer. He can make trade-offs between storage hierarchy and speed of execution.

3. Long-term results. The most important advantage of FORTRAN in this area lies in its generality.

   (a) Documentation is under the control of the individual. There are aids in the form of cross-reference files after the individual has thoroughly set up his comments.

(b) System designers other than the original model developer can easily follow the logic and detail of the simulation with less effort.

(c) Computers of different manufacturers can use the same higher-order language program. Usually there is some requirement for rework; but in terms of the total effort involved, this would be considered minor.

4. Effort required. Less effort is required to carry out the simulation in FORTRAN than it would be for the rest of the General-purpose programming and Simulation languages. Several programmers can work on the simulation model in parallel if the conventions governing the transfer of data between subroutines are well planned in advance. In this respect, a simulation program written in FORTRAN, in modular fashion, can easily be altered by anyone with a working knowledge of FORTRAN, and in particular, parts of the program can be altered without affecting the whole program.

The FORTRAN meets all of the above requirements fairly well and further, its use in this study is also obvious from the TABLE 2.1.

The table shows the relative comparison (Colella, 1974) of various languages for the implementation of discrete simulation. The basis for these weights are subjective, but at least it is an attempt to relate these considerations. The languages mentioned above are merely representative of the vast number that are available.

In the table, each language is given a numerical weight with regard to a specific consideration. The weights are interpreted from 0 to 5 as follows.

0 - not applicable.

1 - very poor.

2 - poor.

3 - fair.

4 - good.

5 - very good.

TABLE 2.1 Comparison of Languages for Discrete Simulation.

	Assembly	FORTRAN	PL/1	GPSS	Simscript
Execution speed	5	4	3	3	2
Memory Utilization	5	4	3	1	2
Availability: User's Library Personnel	5 2	5 4	2 2	3 3	2 2
Program Transferability to other systems	0	4	3	3	3
Application flexibility	5	5	4	2	3
Accuracy of Model Representation	5	5	4	2	4
Simulation Structural Capability	2	3	4	5	5
Programming Diagostic Aid	1	3	3	4	3
Program Documentation Aids	1	3	3	4	4
Program Ease in Formulation	1	4	4	5	4
Total (55)	32	44	35	33	34

CHAPTER THREE

DYNAMIC PROGRAMMING APPROACH FOR OPTIMIZATION

3.1 Introduction

DYNAMIC PROGRAMMING, as an optimizing procedure, has been around for a few years now and perhaps, the main reason that it is still with us arises from Bellman's inexhaustible supply of examples, both realistic and imaginary, which may be analyzed using this approach. A more detailed and comprehensive coverage of dynamic programming can be found in Bellman's three books (1959, 1962, 1965) where his examples and exercises cover almost every form of optimization problem. Dynamic programming is a mathematical technique often useful for making a sequence of interrelated decisions. It provides a systematic procedure for determining the combination of decisions which maximizes/minimizes overall effectiveness. This method is a general type of approach to problem solving, and the particular equations used must be developed to fit each individual situation. Therefore, a certain degree of ingenuity and insight into the general structure of dynamic programming is required to recognize when a problem can be solved by dynamic programming procedures, and how it would be done.

Butches, Haimens, and Hall (1969) and Morin and Esogbue (1971) studied the optimal sequencing and scheduling of water supply projects via dynamic programming, minimizing the present value of the total cost. Nainis and Haimes (1975) expanded the Butcher, Haimes, and Hall (1969) model for the optimal scheduling of construction of multiple project, multiple location of water supply systems. Hall, Haimes, and Butcher (1972) considered the construction of interim projects with limited life times, such as desalination plants via dynamic programming.

Scarato (1969) discussed the time-capacity expansion of water supply systems. Using dynamic programming a policy of expansion is determined to minimize the present value of the total cost. Rachford, Scarato, and Tchobanoglous (1974) apply the above method to wastewater treatment plants. Kaplan and Haimes (1975) have employed the dynamic programming to determine the optimal schedule of expansions of wastewater treatment plant. Some of the shortcomings of the above method are overcome by a method proposed by Riordan (1976), where a dynamic programming is used to determine the optimal policy of capacity expansion, minimizing the present value of the total cost.

Most of the above sources are concerned with water supply and waste water treatment projects and dynamic programming was employed to determine:

1. the optimal schedule of expansion at each plant.
2. the optimal operating policy.
3. optimal allocation of computer registers.
4. optimal control of waste water treatment.
5. optimal design of concrete beams.

In this work a discretized dynamic programming is used to find an optimal quality control of river water. The objective function is to be minimized subjected to the given total available aeration capacity. It works best when the number of decisions at any stage is not too large. Under this condition, it can handle a very large number of stages with comparatively little difficulty. The philosophy of a sequential decision making in the capacity allocation to each of the series of aerators along the stream, the nonlinearities in the DO sag profile and recursive cost function, suggest the use of dynamic programming.

3.2 Characteristics of Dynamic Programming

The principal characteristics of any problem which is amenable to solution by dynamic programming are:

1. The problem can be divided up into stages, with a policy decision required at each stage.

The stream segment under consideration is divided into N reaches. The system is considered to be

made up of a number of connected segments (reaches) in which each reach has constant properties. Reach nodes are, therefore, established at every major or significant change in the system. Significant changes are the discharge point of a waste load, a tributary joining the system, etc. A long section of a stream having acceptable uniform properties should not be divided into two or more reaches because of its length. The policy decision at each stage (reach) is the amount of aeration V(i) needed for that particular stage.

2. Each stage has a number of states associated with it and each state corresponds to a possible condition which the decision variable might take at any particular stage.

The state associated with each stage is the state variable, D(i), discretized into M values with C(S) as its maximum and zero as its minimum value. In general, the states are the various possible conditions in which the system might find itself at that stage of the problem. The number of states may be either finite, as in this case, or infinite.

3. The effect of the policy decision at each stage is to

transform the current state into a state associated with the next stage.

The dynamic programming problems can be interpreted in terms of network. Each node would correspond to a state. The network would consist of columns of nodes, with each column corresponding to a stage, so that flow from a node can go only to a node in the next column to the right. The number assigned as the "distance" between connected nodes can be interpreted as the amount of aeration needed to go from one stage to another. Now, the objective would be to find the route through the network which minimizes the amount of aeration, and in turn minimizes the objective function.

4. Given the current state, an optimal policy for the remaining stages is independent of the policy adopted in previous stages.

Given the state in which one is currently located, the optimal aeration capacity policy from this point onward is independent of how we got there. since the knowledge of the current state of the system conveys all of the information about its previous behaviour necessary for determining the optimal policy henceforth.

5. The solution procedure begins by finding the optimal policy for each state starting from the last stage.

6. A recursive relationship is available which identifies the optimal policy for each state with n stages remaining, given the optimal policy for each state with n-1 stages to go.

   Therefore, finding the optimal policy when starting in state s with n stages to go required finding the minimization value of D(n). This policy would consist of using the value of D(n) and thereafter following the optimal policy when starting in state D(n) with (n-1) stages to go.

7. Using the recursive relationship, the solution procedure moves backward stage by stage - each time finding the optimal policy for each state of that stage - until it finds the optimal policy of N-stage system.

8. The N-stage optimal policy is found by passing forward through the system.

3.3 Philosophy of Dynamic Programming Technique

How does all of the above characteristics fit in with the river pollution problem?

Consider a river basin containing one major stream and several industries and municipalities located adjacent to the stream as shown in Figure 3.1. The waste discharged to the stream is assumed to be characterized by its BOD. To meet specified DO standards for the stream as efficiently as possible, decisions have to be made regarding levels of treatment at each of the N outfalls. It should be apparent that the river system can be divided into a set of N discrete reaches or stages with a decision being required at each as shown in Figure 3.2. It should be noted that numerous conditions other than waste discharge can and should constitute stage or reach doundaries, e.g.,significant tributary flows, change in temperature, change in flow conditions, etc. These cause no difficulty, however, but will not be considered in this application.

The state of a reach or stage consists of the BOD and DO entering at the upstream end of the stage. There are obviously an infinite number of possible states or incoming BOD and DO combinations for each stage. The range of incoming BOD and DO is divided into discrete values as shown in Figure 3.3.

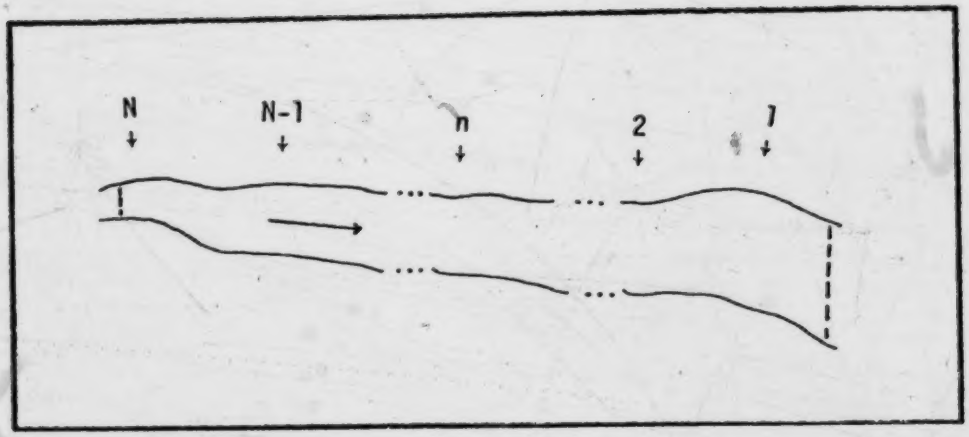

FIGURE 3.1: Schematic Illustrating a Typical River Basin and Waste Outfalls.

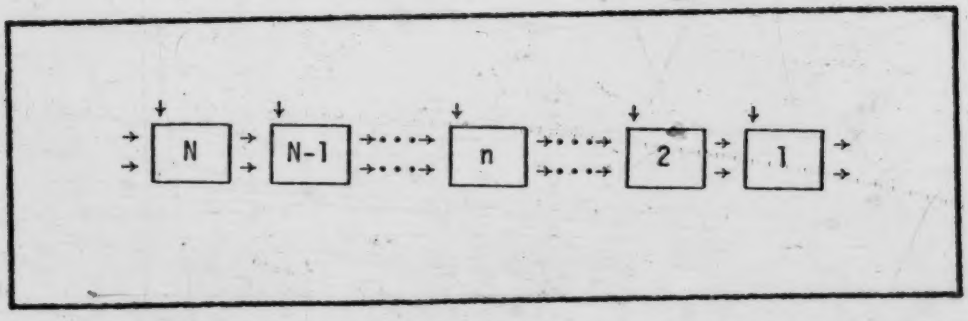

FIGURE 3.2: Schematic Illustrating a Typical River Basin and Waste Outfalls as an N-Stage Process.

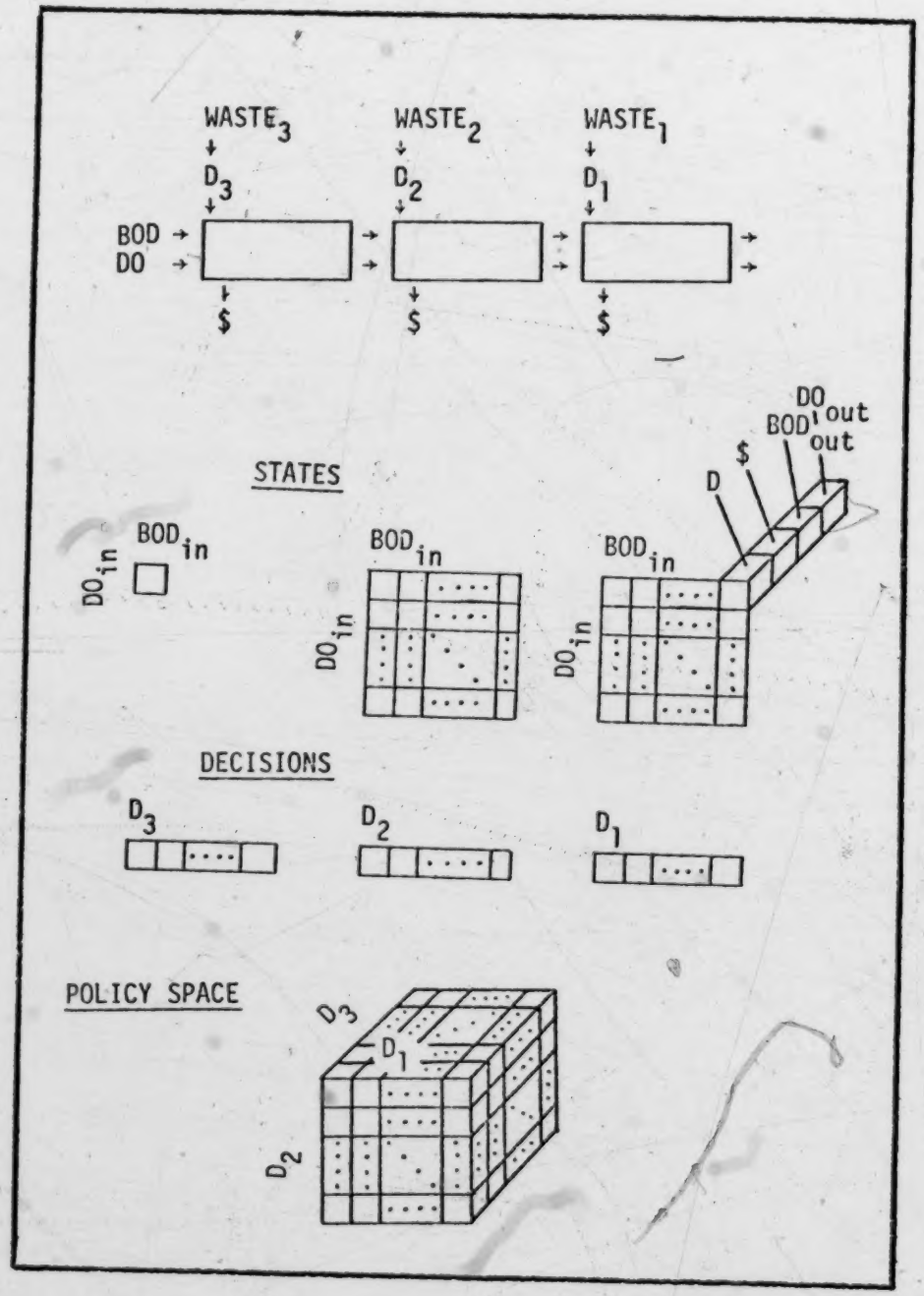

FIGURE 3.3: Schematic Illustrating Discrete States and Decisions for a 3-Stage Process.

TABLE 3.1: Number of Possible Policies as a Function of Number of Stages and Treatment Increments.

INCREMENT ON TREATMENT %	NUMBER OF STAGES					
	1	2	3	4	5	6
1	101	10,201	1.03E06	1.04E10	1.56E10	1.06E12
2	51	2,601	132,651	6.76E6	3.45E8	1.76E10
5	21	441	9,261	194,481	4.08E6	8.60E7
10	11	121	1,331	14,641	161,051	1.77E6
20	6	36	216	1,296	7,776	47,000

For example, if incoming BOD could vary from 0 to 20 mg/l at stage n one might select to use values of 0, 2, 4, ..., 20 mg/l. If incoming DO could vary from 0 to 9 mg/l at stage n one might use 0, 1, 2, ..., 9 mg/l. This would result in 110 possible discrete states at stage n. One may use increments as small as desired. It is assumed that the BOD and DO entering the upstream is known.

At each stage a decision regarding treatment[2] must be made. This can vary from 0 to 9 mg/l. The consequences as regard cost and quality must be investigated for the whole allowable range. As with the input BOD, discrete levels are used, e.g., 0, 5, 10, ..., 100 mg/l and DO can vary from 0, 1, 2,....,9 mg/l. Large or smaller increments may be used. The relationship between number of stages, treatment increment, and number of possible N-stage policies is shown in Table 3.1. There are an infinite number of possible policies. Simple preliminary screening can reduce the number of possible policies greatly. Even if the reduction is several orders of magnitude, there would be too many alternatives to investigate without a dynamic programming approach.

Transfer functions are required to determine the BOD and DO leaving stage n (and entering stage n-1) as a result

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[2] Amount of aeration required at each stage.

of being in a given state (incoming BOD and DO) and the decision regarding treatment as shown in Figure 3.4. One may use transfer functions as complex and realistic as desired. For this application, the basic Streeter-Phelps (1925) equations for BOD and DO are used.

$$BOD_t = BOD_A e^{-k_1 t} \tag{3.1}$$

$$DO_t = C_s - \frac{k_1 L_A}{k_2 - k_1} (e^{-k_1 t} - e^{-k_2 t}) + D_A e^{-k_2 t} \tag{3.2}$$

BOD_A, the initial BOD at the top of the stage, is an average of the incoming BOD (BOD_{in}) and the BOD discharged (BOD_{dis}) at the outfall:

$$BOD_A = f(BOD_{in}, BOD_{dis}) \tag{3.3}$$

Since BOD_{in} is part of the state or input conditions to the stage and BOD_{dis} is a discrete function of the treatment level. Then one can rewrite the above equation as:

$$BOD_{in} = f(state, decision) \tag{3.4}$$

Similarly, the DO should be an average of the incoming DO (DO_{in}) and the DO in the waste (DO_{dis}).

$$DO_A = f(DO_{in}, DO_{dis}) \tag{3.5}$$

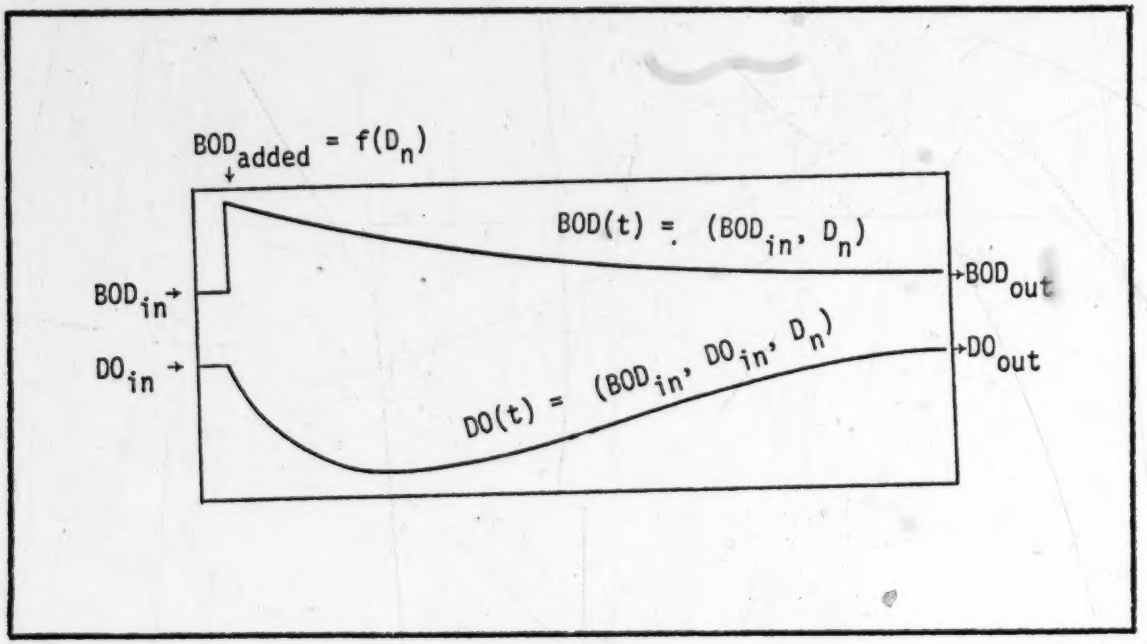

FIGURE 3.4: Schematic of a Typical Stream Reach or Stage Illustrating Transfer Functions for BOD and DO.

Again, DO_{in} is part of the state. It is assumed that there is a negligible amount of DO (DO_{dis}) in the Waste. But for sake of generality, the transfer equation can be rewritten as:

$$DO_A = f(\text{state, decision}) \tag{3.6}$$

The initial DO deficit, D_A, is then:

$$D_A = C_s - DO_A = f(\text{state, decision}) \tag{3.7}$$

Now by substituting BOD_A and D_A from equations 3.3 and 3.7 into the BOD and DO transfer functions, equations 3.1 and 3.2, the BOD and DO at any point within a stage is a function of the state, or input BOD and DO, and the treatment decision.

$$BOD_t = f(\text{state, decision}) \tag{3.8}$$

$$DO_t = f(\text{state, decision}) \tag{3.9}$$

Ey determinig the DO at the Sag[2] point, one may determine, for any state, whether the DO standard has been violated as a result of various treatment level decisions. If the standard is violated, then any policy which include that state and that decision would be infeasible and need not be considered further.

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[2] Defined in Appendix-B

When Tf equals the time-of-flow in the stage, the output BOD and DO are given by:

$$BOD_{out} = BOD_A e^{-k_1 Tf} \tag{3.10}$$

$$DO_{out} = C_s - \frac{k_1 BOD_A}{k_1 - k_2} (e^{-k_1 Tf} - e^{-k_2 Tf}) + D_A e^{-k_2 Tf} \tag{3.11}$$

Each of these two output components could be components of the state for the downstrem reach. It should be clear now that the transfer functions enable one to determine the next state frcm the present state and the decision.

Given a particular state or input BOD and DO, the optimal policy for the downstream reaches is independent of the upstream decisions that may have lead to this state.

The solution process begins at the downstream stage (stage 1) and moves upstream. Given all possible states or combinations of BOD and DO which could enter the top of stage 1, one simply determines the lowest, and most economical, level of treatment which will prevent a viclation of the DO standard. The treatment level and its cost are stored with the state for future use.

At stage 2 all possible states or combinations of BOD and DO entering the top of stage 2 are considered. For each

of these states, the entire range of treatment at stage 2 must be investigated. The quantity which is to be minimized is the sum of treatment costs at stages 2 and 1. Selection of a treatment level at 2 allows one to know the local cost, as cost is a function of treatment level. If the level of treatment being considered does not cause a DO standard violation in stage 2, then the output BOD and DO are determined. Knowledge of these values enables one to go to the appropriate state in stage 1 and retrieve the optimal 1-stage cost. The entire range of treatment levels for each state of stage 2 is used, and the level which results in the least 2-stage cost is the optimal treatment decision for the given state of stage 2. Other possible states of stage 2 are investigated in a similar manner. For stage 2 (and all other upstream stages), the optimal treatment level, the optimal total cost up through that stage, and the output BOD and DO are stored for each state.

When one reaches stage 3, the information about stage 1 will not be used directly, as it is incorporated in the 2-stage information. In general, all that will be needed at stage n will be the information previously obtained for an (n-1)-stage system.

When the upstream (Nth) stage is reached, there will be only one possible state as this is an initial-value problem. For this single state, all treatment decisions will be

considered. The quantity being minimized being the N stage local cost and the (N-1)-stage optimal cost for the resulting state or stage (N-1).

The decision at stage N which yields the minimum total N-stage cost is then the Nth component D(N) of the N-stage optimal policy *D(N). The output BOD and DO resulting from the optimal treatment level of stage N allow one to go directly to the approprite state of stage (N-1) and select the next component *D(N-1) of the N-stage optimal policy. This 'forward pass' continues until the first stage is reached.

At this point, it would be appropriate to mention that dynamic programming is simply an approach to be used in optimizing serial systems. Dynamic programming is unlike linear programming in that there is no standard mechanical procedure for structuring and solving a problem. For example, in most real world applications, one must determine the form of the recursive relationship. Much is left to the individual in applying the technique successfully.

CHAPTER FOUR

MATHEMATICAL MODEL OF THE SYSTEM

4.1 Introduction

In this chapter, the rationale, concepts, and mathematical models for the simulation of water quality in a river system are developed. Emphasis is placed upon the theoretical aspects.

The simulation model is made up of a group of mathematical equations which are linked together by a progammed logic. The purpose of the model is to generate a reasonably accurate representation of the stream flow and oxygen balance in a river system. The model determines the mean and standard deviation from the historical data for each waste disposal station. The historical data are daily gage records from gaging stations located at the top of each reach. The model simulates quantity of waste flow into the river system using the mean and standard deviation computed from historical data for each reach[1]. The value of the simulation model depends to a great extent upon the use of high-speed digital computer for fast and accurate

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[1] Described in detail in section 5.3. 'Preparation for Simulation'.

computations and application of logic. The speed of the computer not only provides the results within an acceptable time but also reduce materially the costs to obtain the results. In short, the computer is a necessary appurtenance in the use of the simulation model. For this reason, the development of models, techniques and logic is made for direct application of computer methods.

A system in which there are several waste dischargers is considered to be divided into reaches, with continuously treated or untreated waste discharged into it. The reach is defined as the stretch of a stream between two dischargers. The last reach encompasses the remainder of the stream from the last discharger to the end of the segment under consideration. The optimal allocation of artificial aeration equipment along the section is to be determined. This is done by starting with the Streeper-Phelps model (1925) and by making appropriate simplifying assumptions such as constant river coefficients, steady-state one dimensional flow, small effect of second stage biochemical oxygen demand, negligible dispersion effect and photosynthesis.

4.2 Theoretical Model

The first dissolved oxygen model for predicting oxygen balance in a flowing stream was presented by Streeter and Phelps. For the present work, the simple first-order decay function is used for BOD (4.1) and the Streeter-Phelps model is used for DO (4.2).

$$-\frac{dl}{dt} = L_0 e^{-k_1 t} = L_t \qquad (4.1)$$

$$-\frac{dc}{dt} = k_2 (C_s - C_t) - k_1 L_t \qquad (4.2)$$

It is evident that any particular solution to equation 4.1 is independent of equation 4.2, whereas the solution to equation 4.2 dependent upon the solution to equation 4.1. That is, the BOD profile is independent of the oxygen profile, but the oxygen profile depends upon the BOD profile.

Combining equations 4.1 and 4.2, we have

$$-\frac{dc}{dt} = k_2 C_s - k_2 C_t - k_1 L_0 e^{-k_1 t} \qquad (4.3)$$

With artificial aerator at point t_{i-1} and subjected to the following boundry conditions:

$$C_t = C_0 \quad \text{at } t=0$$

$$C_i - C_{i-1} = V_i \quad \text{at } t = t_{i-1} \tag{4.5}$$

the DO concentration at any time t is given by the following Streeter-Phelps equation.

$$C_t e^{k_2 t} = C_s(e^{k_2 t} - 1) - \frac{k_1 L_0}{k_2 - k_1}(e^{(k_2 - k_1)t} - 1) + C_0 + V_i e^{k_2 t_{i-1}} U_i \tag{4.6}$$

The rate of oxygen absorption, U, by stream water depends on numerous interacting factors, such as water temperature, flow condition, characterstics of water and type of air applied. According to O'Connor and Dobbins (1956), the rate of oxygen supply by an aerator device is represented by

$$U = K_v (C_s - C_t)$$

where K_v is the volumetric absorption rate coefficient of oxygen. This depends on the stream temperature. Morgan and Bewtra (1960) carried out an experiment with compressed air to evaluate K_v at 20°C and found the value to be 34.88 for their specific equipment. Then the rate of artificial aeration absorption term of Morgan and Bewtra can be represented as

$$U = 34.88(1.024)^{(t-20)}(C_s - C_t)$$

The following equation is obtained by just rearranging the equation 4.6.

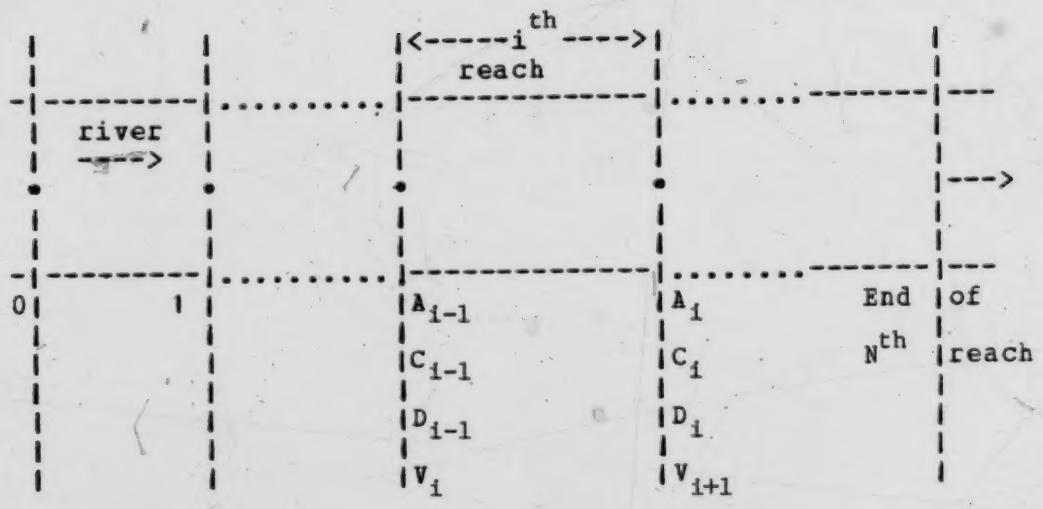
$$(C_s-C_t)e^{k_2t} = (C_s-C_0)+\frac{k_1L_0}{k_2-k_1}(e^{(k_2-k_1)t} - 1) - U_i V_i e^{k_2t_{i-1}} \qquad (4.7)$$

By introducing the DO deficit instead of DO concentration, equation (4.7) becomes:

$$D_t = D_0e^{-k_2t} + \frac{k_1L_0}{k_2-k_1}(e^{-k_1t} - e^{-k_2t}) - U_i V_i e^{-k_2(t-t_{i-1})} \qquad (4.8)$$

This is the governing equation for DO sag profile along a stream with a point aeration source at (i-1)

For dynamic programming formulation convenience, the river segment under consideration is divided into N reaches, the i^{th} reach stretches from t_{i-1} to t_i. The length of reach equals $(t_i - t_{i-1}) = X_i$ (days). Assume that aerators $A_0, A_1, A_2, \ldots\ldots, A_{N-1}$ are located at 0, 1, 2,....., i,.... N-1, the top of each of N reaches. For simplicity, capacities of these aerators are assumed to be equal to the increment in level of DO needed at those points, they are $V_1, V_2, \ldots\ldots, V_i \ldots . V_N$. The Figure 4.1 gives the schematic representation of the system.



• - Waste discharge point

Figure 4.1 Schematic representation of the system.

The DO deficit at any point P within the reach i can be computed by equation (4.9) where D_{i-1} is the initial DO deficit for this reach.

let $p \geq 0$ and $p \leq X_i$ days.

$$D_{i-1+p} = D_{i-1} e^{-k_2 p} + \frac{k_1 L_{i-1}}{k_2 - k_1} (e^{-k_1 p} - e^{-k_2 p}) - U_i V_i e^{-k_2 p} \qquad (4.9)$$

Where $0 \leq p \leq X_i$

At the end point of this reach, $P = X_i$, the DO deficit becomes D_i.

$$D_i = (D_{i-1} - V_i U_i) e^{-k_2 X_i} + \frac{k_1 L_{i-1}}{k_2 - k_1} (e^{-k_1 X_i} - e^{-k_2 X_i}) \qquad (4.10)$$

Again from reach to reach the BOD changes. The BOD concentration at the top of each reach depends on the quantity of waste added at that point. Accordingly, the DO deficit varies. The BOD concentration at the end of the reach is given by

$$L_{i-1} = L_{i-2}e^{-k_1X_{i-1}} = L_{i-3}e^{-k_iX_{i-2}}\, e^{-k_1X_{i-1}} = \ldots\ldots$$

$$= L_0\, e^{-(i-1)X_ik_1} \qquad (4.11)$$

Where L_0 is the initial BOD (BOD_{in}) level plus the BOD (BOD_{dis}) added at the top of the reach. Substituting equation (4.11) into equation (4.10) gives

$$D_i = (D_{i-1} - U_iV_i)\, e^{-k_2X_i} + \frac{k_1L_0e^{-(i-1)k_1X_i}}{k_2 - k_1}\,(e^{-k_1X_i} - e^{-k_2X_i}) \qquad (4.12)$$

This equation gives the DO deficit at the end of the i^{th} reach. The deficit should not be less than the standard value specified by the authorities. In order to maintain the value of DO greater than or equal to the specified value (5 mg/l), artificial aeration should be provided at the top of this reach. We must provide aeration to the stream in such a way that the specified law value ($C \geq 5$mg/l) should be maintained for all parts of the stream in that reach. No distinction is made between day time and night time operation.

The capacity of aerator located at A can be computed from equation (4.12), provided that the value of D_0 and D_1 are specified, and all other constant and coefficients are given, that

$$V_i = \frac{k_1 L_0 e^{-(i-1)k_1 X_i}}{k_2 - k_1} (e^{(k_2-k_1)X_i} - 1) + D_{i-1} - D_i e^{k_2 X_i} + U_i \qquad (4.13)$$

The above equation gives the amount of aeration needed to keep the DO level above the specified value in that reach. Otherwards the capacity of aerators at the top of the i^{th} reach.

4.3 The Objective Function and Constraints

The seccnd objective is to define the objective function to achieve the artificial aeration at minimum cost. For this aeration problem the mathematical form of the objective function is written as

$$Z = \sum_{i-1}^{N} W_1 (C_i - C_\ell)^2 + W_2 V_i^2 \qquad (4.14)$$

Where W_1 and W_2 are weighting factors ($W_1 > 0$, $W_2 > 0$ and $W_1 + W_2 = 1$) and N is the number of aerators used in the system.

The first term represents the weighted sum of the squares of the specified law value of DO, and the actual DO level C_i. The objective function should taken on a zero value whenever the specified law value is reached for all time. The corresponding value of V_i would also be zero. Whenever $(C_i - C_\ell) = 0$, the objective function should always be positive. If $C_i < C_\ell$, damaging cost for the environment is incurred and if $C_i > C_\ell$, unnecessarily providing aeration cost is imposed. The costs can be either the time cost in dollars per unit DO level, if any estimation method is available in the literature or the nominal costs used in a typical objective function in the control problem.

The use of weighting factors in the objective equation provides the planner a planning flexibility. For instance, if the designer's main concern is to satisfy the stream standard, then he can select W_1 in such a way the ratio W_1/W_2 is a large number or if the main concern is the cost for providing artificial aeration and the water quality is permitted to deteriorate at certain points along the stream, then he can choose W_2 such that W_2/W_1 is large. Hence by varying different combinations of the values of W_1 and W_2 provides the designer a designing flexibility.

since $(C_i - C_\ell) = (C_s - C_\ell) - (C_s - C_i) = D_\ell - D_i$, equation (4.14) can be expressed in terms of DO deficit, that is

$$\underset{v}{\text{Minimize}} \quad Z(D,V) = \sum_{i=1}^{N} W_1 (D_\ell - D_i)^2 + W_2 V_i^2 \qquad (4.15)$$

By employing equation (4.15) the mathematical model of our problem can be formulated as follows:

$$\underset{v}{\text{Minimize}} \quad Z(D,V) = \sum_{i=1}^{N} W_1 (D_\ell - D_i)^2 + W_2 V_i^2 \qquad (4.16)$$

Subjected to:

1. The limitation on total available aeration capacity

$$\sum_{i=1}^{N} V_i \leq Y \qquad (4.17)$$

where Y is the available aeration capacity.

2. Physical limitation on DO deficit and aeration capacity.

$$0 \leq D_i \leq C_s \qquad (i = 1, 2, \ldots\ldots, N) \qquad (4.18)$$

$$0 \leq V_i \leq C_s \qquad (i = 1, 2, \ldots\ldots, N) \qquad (4.19)$$

By introducing a Lagrange multiplier ϵ ($\epsilon \geq 0$), which has the significance of a price (Bellman, 1962), the modified objective function equation (4.20) with constraints (4.21) and (4.22) below is equivalent to the original problem (equation 4.16, 4.17, 4.18 and 4.19) (Everett, 1963), where Y equales ΣV_i found in the modified problem.

$$\underset{v}{\text{Minimize}} \quad Z(D,V) = \sum_{i=1}^{N} W_1(D_\ell - D_i)^2 + W_2 V_i^2 + \epsilon \sum_{i=1}^{N} V_i \qquad (4.20)$$

Subjected to:

$$0 \leq D_i \leq C_s \qquad (4.21)$$

$$0 \leq V_i \leq C_s \qquad (4.22)$$

Since the optimal policy of the modified problem is a function of ϵ, We can find a proper value of ϵ by interpolatien to force the optimal policy to satisfy the level of Y desired in constraint (4.17).

4.4 Derivation of the Recurrence Relation

Once the objective function has been formulated, the next step in the mathematical formulation centers around in developing the recurrence relation.

As defined before, the reach of interest is divided into N stages where stage i corresponds to the end of reach i. Let D_i be the state variable at stage i, it is the DO deficit at point t_i and V_i be the decision variable at stage i, it is the DO increment needed at point i - 1, when D_{i-1} and D_i are specified.

The stage transformation equation T can be derived from equation (4.10)

$$D_{i-1} = T[D_i, V_i]$$

or

$$D_{i-1} = D_i e^{k_2 X_i} + V_i - \frac{k_1 L_0 e^{-(i-1)X_i k_1}}{} (e^{(k_2-k_1)X_i} - 1) \qquad (4.24)$$

The recursive formula is:

$$Z_N(D_N, \theta) = \min_{V} \{W_1 (D_\ell - D_N)^2 + W_2 V_N^2 + \theta V_N + Z_{N-1}(D_{N-1}, \theta)\} \qquad (4.25)$$

With the following conditions

$$0 \leq V_N \leq C_s \qquad (4.26)$$

$$0 \leq D_N \leq C_s \tag{4.27}$$

The objective function for the first stage becomes:

$$Z_1(D_1,G) = \min_{V_i} \; W_1(D_1 - D_i)^2 + W_2 V_i^2 + G V_i \tag{4.28}$$

where

$$0 \leq V_i \leq C_s \tag{4.29}$$

$$0 \leq D_i \leq C_s \tag{4.30}$$

In equation (4.25) the subscript N represents the number of stages remaining in the process; the vector D_N describes the state of the process with N stages remaining; the function $Z_N(D_N,G)$ is the yield from an N stage process starting at state S and employing an optimal policy; V_n is the class of all admissible policies or decisions; $Z_{N-1}(D_{N-1}, G)$ is the yield during the first stage of the N stage process and depends upon decision V_n. Mathematically, we have said, if one knows the immediate effect of a decision over the next time interval and the long-range effect from the end of that time interval until the end of the process, then one knows the effect of that decision from the present until the end of the process. This is precisely the total return over the process.

CHAPTER FIVE

APPLICATION TO NORTH SASKATCHEWAN RIVER

5.1 Introduction

The simulation model, including the data generator, was applied to the North Saskatchewan River near Edmonton, Alberta, Canada. This river holds an unique position among the major rivers on the North American continent in that, as a major source of water supply and as a receiver of municipal and industrial waste water (Figure 5.1), it is completely frozen over during the winter for a periods averaging five months. During this period of ice cover, minimum discharges also occur in the river.

During the winter of 1955-56, the DO level 100 miles downstream from Edmonton was zero (Figure 5.2). This led to an attempt to artificially aerate the river (Department of Public health, 1956). With the cooperation of the city of Edmonton and the Provincial Department of Public Works, the Sanitary Engineering Division of the Department of Public Health, set up an air compressor system near Redwater, Alberta in an attempt to artificially raise the dissolved oxygen levels in the river. The operation continued for eighteen days, at which time, melting conditions made it necessary to remove equipment from the ice. During the

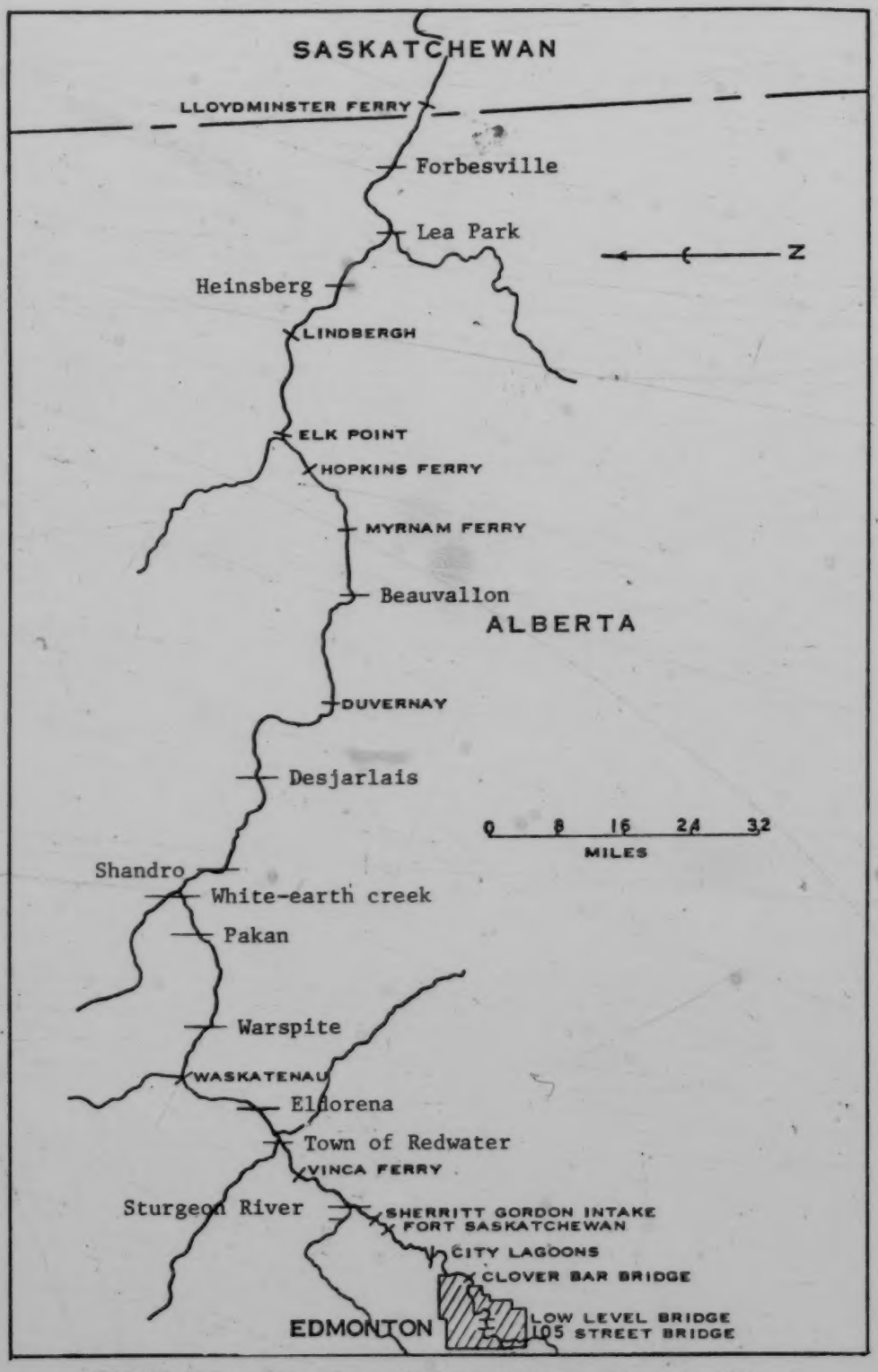


FIGURE 5.1: Map of North Saskatchewan River in Alberta and Waste Outfalls on the River Banks.

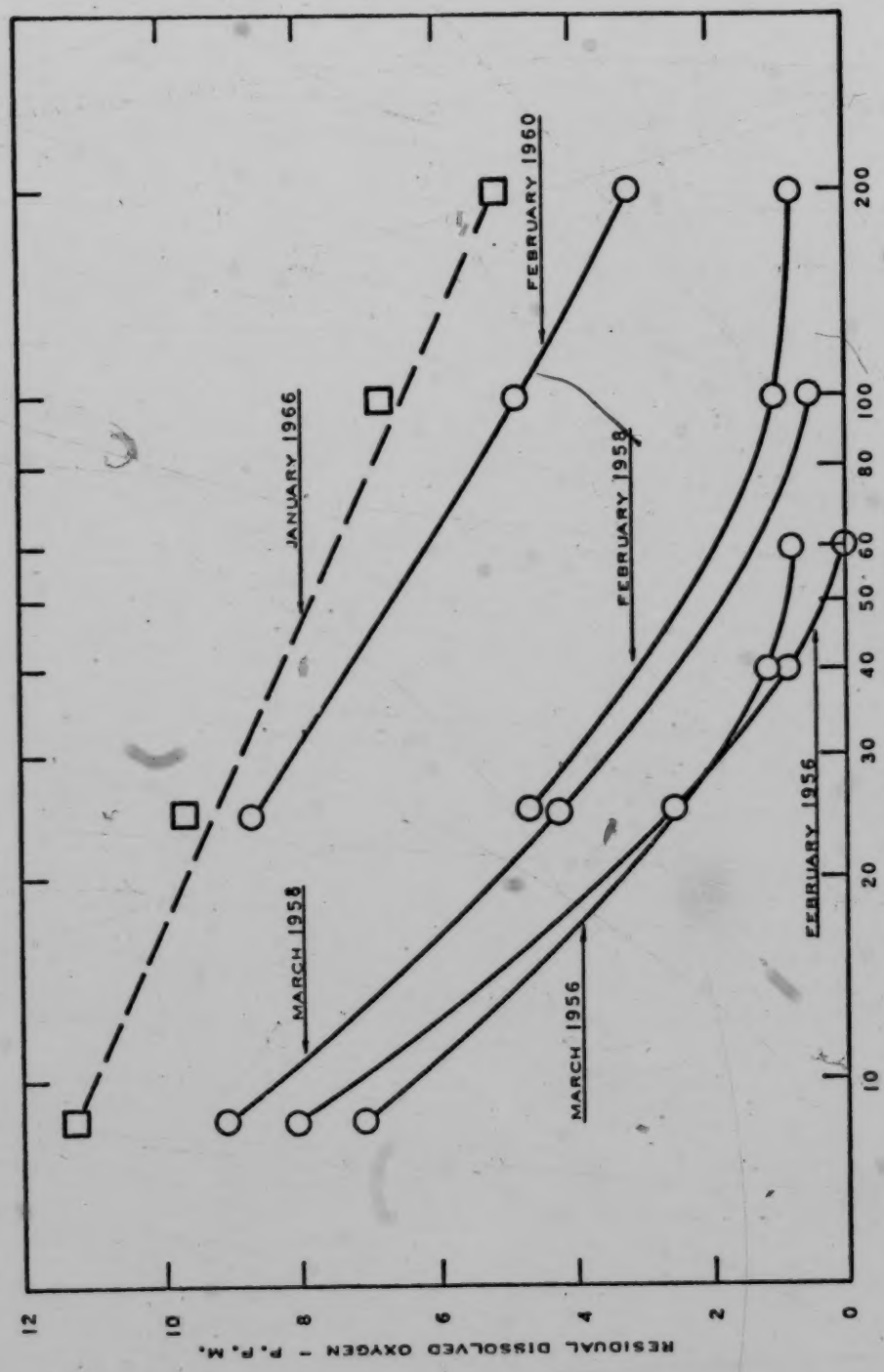


FIGURE 5.2: RESIDUAL DISSOLVED OXYGEN
NORTH SASKATCHEWAN RIVER
DATA FROM THE ALBERTA GOVERNMENT SANITARY
ENGINEERING DIVISION

continuous operation, a raise of only 0.25 mg/l in dissolved oxygen (DO) level was observed immediately downstream from the aeration system. No increase in DO was observed further downstream. This led to the introduction, by the Alberta Division of Environmental Health Services, of stringent control of all wastes discharged to the river. As a result of this pollution abatement program, improved dissolved oxygen levels have been maintained in the river. This has been brought about by the construction of the primary treatment section of a new sewage treatment plant, augmented in 1957 by the use of secondary treatment facilities at this plant. In 1961, Brazeau Dam was constructed to provide storage for winter release to improve water quality during winter months. In 1965, sewage lagoons were constructed for winter storage for meat packing plant wastes and some domestic sewage. The use of these lagoons, sewage treatment plant, and low flow augmentation dam have further reduced the waste loading on the river.

5.2 River Flow and Its Usage

The North Saskatchewan River is characterized not only by its relatively long period of ice cover but also by the wide variation between maximum and minimum daily flows. This is shown in Figure 5.3a, 5.3b and Table 5.1. Due to this broad variation in flow and continuous constant daily waste discharge into the river system makes it difficult to maintain the quality of water throughout the year. This uncertainity in river condition is an ideal problem for investigation by simulation.

Further, this river serves as a source of water supply for domestic consumption, agricultural and manufacturing processes and as a receiver and carrier of domestic and industrial wastes. Table 5.2 lists the major users of the river in the province of Alberta.

Because of its large population and industrial complex, the city of Edmonton is the source of major pollution load to the North Saskatchewan River in Alberta. The main source is the domestic sewage effluents from the main and No.3 sewage treatment plants.

A series of sewage lagoons are located 16 miles downsteram from the low level bridge at Edmonton. These lagoons receive domestic and meat packing house wastes from

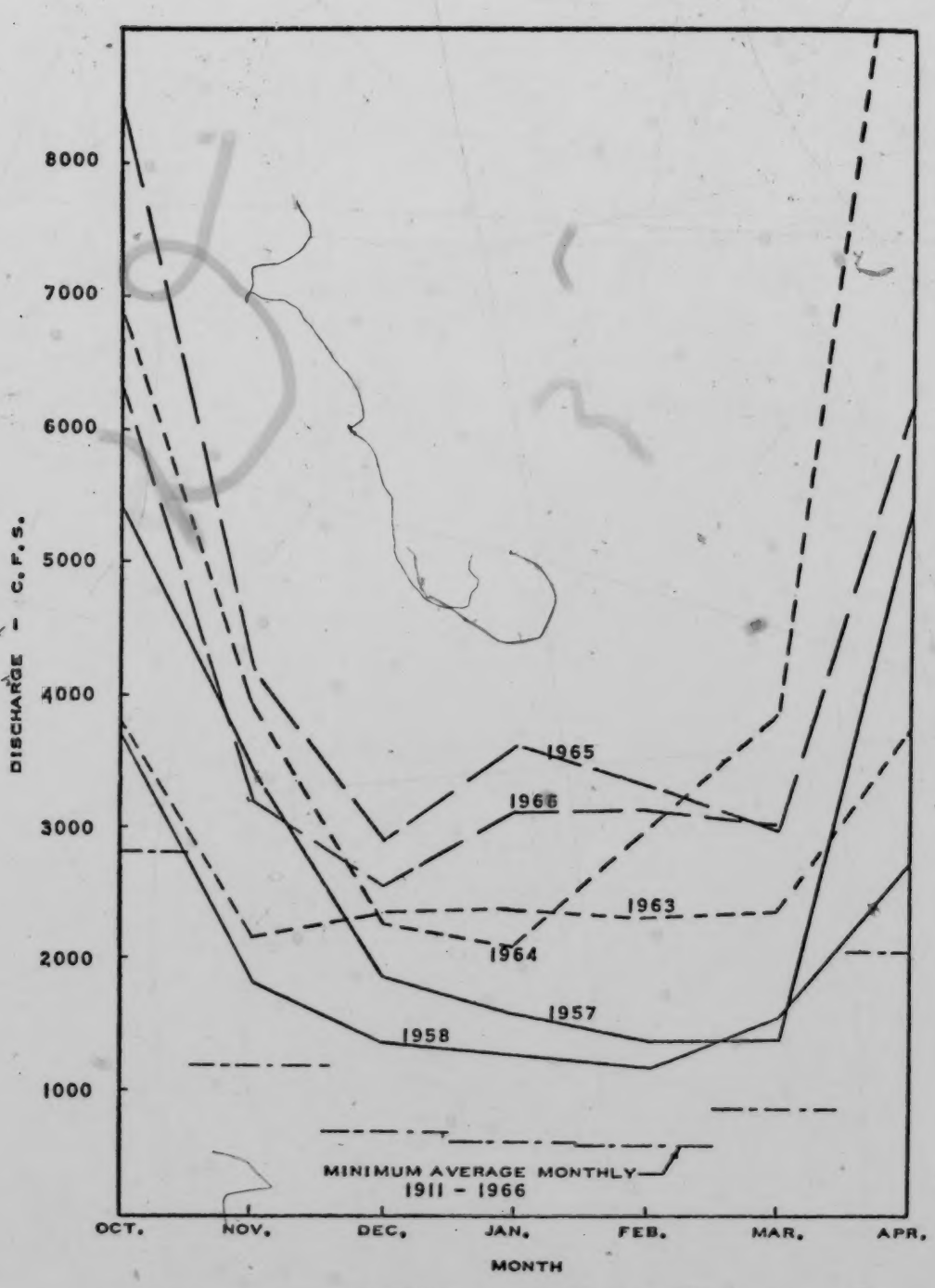


FIGURE 5.3: AVERAGE MONTHLY FLOW
NORTH SASKATCHEWAN RIVER
DATA FROM FEDERAL DEPARTMENT OF WATER RESOURCES

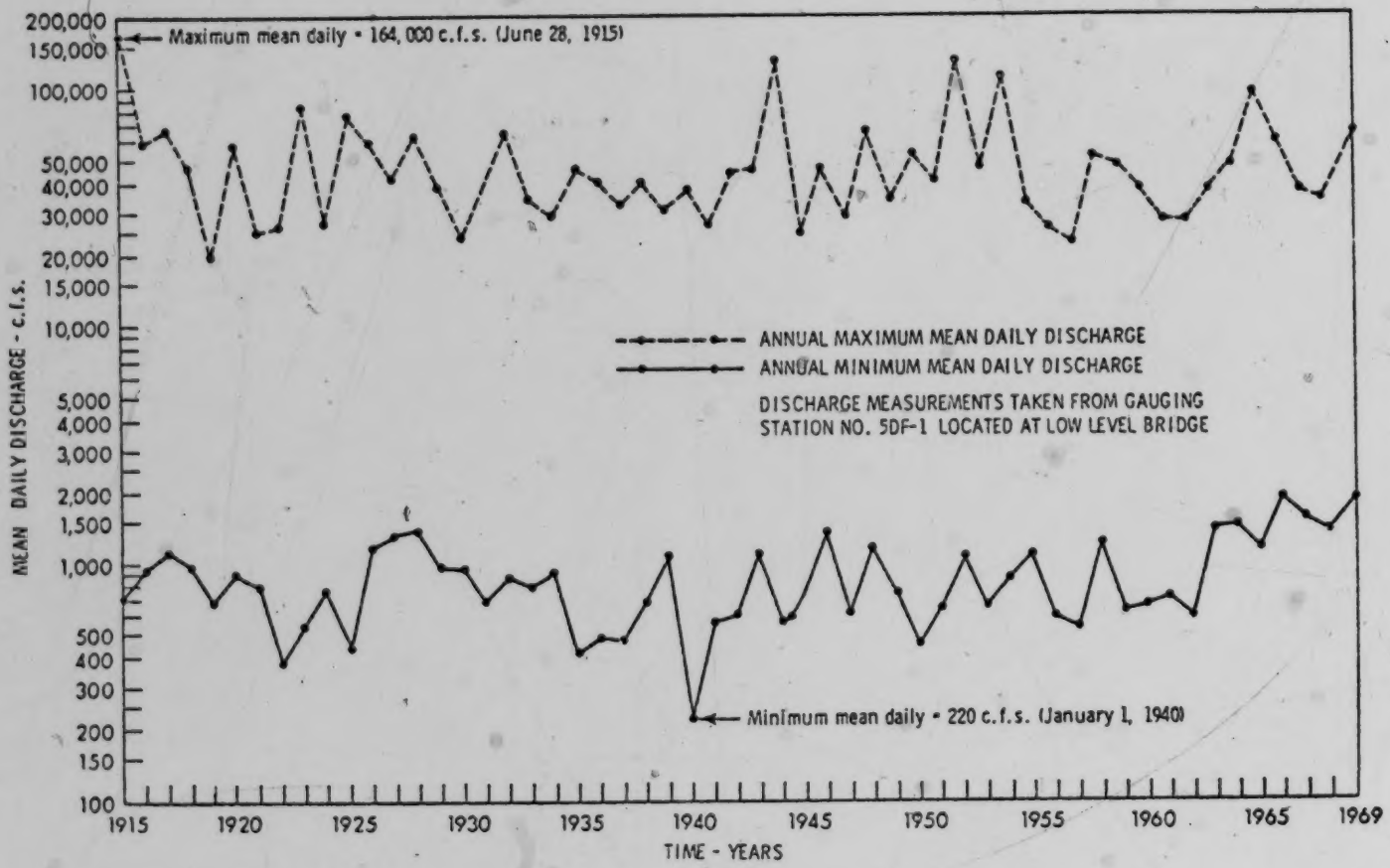


FIGURE 5.3B ANNUAL MAXIMUM AND MINIMUM MEAN DAILY DISCHARGES IN NORTH SASKATCHEWAN RIVER AT EDMONTON - 1915 to 1969

the northeast section of the city and domestic wastes from the hamlet of Sherwood Park, is one of the major users of this river.

The Edmonton industrial complex, consisting mainly of the petroleum and chemical industries, use the North Saskatchewan River as a source for water supply, cooling process and as a receiver of industrial waste effluents. In the past, these industrial wastes have been the main cause of taste and odor problems found downstream from Edmonton.

Recreational use of the North Saskatchewan River in Alberta is restricted to boating and some sport fishing. There is no commercial fishing undertaken in this river in Alberta.

TABLE 5.1

NORTH SASKATCHEWAN RIVER DISCHARGES

(Information from the Federal Water Resources Branch)

YEAR	Maximum instantaneous discharge c. f. s.	Maximum daily discharge c. f. s.	Date of maximum daily discharge	Minimum daily discharge c. f. s.	Date of minimum daily discharge
1911		51442	Jul. 3	984	Nov. 12
1912		74100	Jul. 10	1062	Mar. 25
1913		32600	Aug. 15	1210	AP. 6
1914		61740	Jun. 9	650	Dec. 24-26
1915	204500	164000	Jun. 29	700	Dec. 15
1916	61600	58800	Jun. 22	950	Mar. 4
1917		65597	May 18	1100	Feb. 22
1918		35347	Jun. 16	960	D.12-Fe.20
1919		19885	Jun. 24	688	Mar. 4
1920		57220	May 10	895	Dec. 4
1921	27400	24888	May 23	800	Dec. 23
1922	28600	25760	Aug. 18	380	Nov. 25
1923	99600	84100	Jun. 25	540	D.12,J.11
1924	27600	27500	Jul.5-6	760	Jan. 24
1925	77000	75800	Aug. 18	538	Feb. 26
1926		58700	Sep. 4	1140	Jan. 19-31
1927		40400	Jun. 29	1290	Dec. 16-18
1928		61200	Jul. 7	1330	Nov. 13
1929		38100	Jun. 5	965	J.19-F.2
1930	23900	23700	Jul. 17	952	J.16-F.14
1931		39200	Jul. 2	700	Mar. 16
1932		66000	Jun. 4	865	Mar. 14
1933		34400	Jun. 19	796	Dec. 13
1934		28100	Jun. 1	900	Mar. 2
1935		46300	Jul. 11	406	Jan. 3
1936		40400	Apr. 19	485	Apr. 4
1937		31500	Jul. 17	480	D.23,J.3
1938		40000	Jul. 4	682	Feb. 4,14
1939		30200	Jun. 28	1030	Mar. 3-5
1940		35700	Apr. 18	220	Jan. 1

(Cont. TABLE 5.1)

YEAR	Maximum instantaneous discharge c. f. s.	Maximum daily discharge c. f. s.	Date of maximum daily discharge	Minimum daily discharge c. f. s.	Date of minimum daily discharge
1941		26720	Jun. 28	548	Nov. 17
1942	43960	42250	Jul. 14	583	Nov. 26
1943		44020	Apr. 12	1080	Feb. 10-13
1944	125900	121970	Jun. 16	551	Nov. 22
1945	25060	24300	Jun. 1	724	Nov. 30
1946		44760	Jun. 24	1300	Feb. 8
1947		28600	Jun. 13	602	Nov. 27
1948	66620	65440	May 25	1140	Feb. 12
1949		32680	Jul. 22	730	Dec. 14
1950	53720	50330	Jun. 17	430	Dec. 13
1951	40980	39020	May 3	624	Nov. 25
1952	132000	125000	Jun. 25	1030	Dec. 23
1953	45800	44900	Jun. 5	652	Nov. 29
1954	118400	106600	Jun. 8	833	Apr. 8
1955	32020	30380	Jun. 15	1040	Jan. 5
1956	26600	25460	Jun. 7	580	Nov. 20
1957	23380	21780	Jun. 11	506	Dec. 13
1958	52130	49890	Jul. 1	1180	Jan. 7-8
1959	51740	46140	Jan. 29	598	Dec. 14
1960	38810	36830	Jul. 3	640	Nov. 20
1961	30100	27210	Jul. 31	700	Nov. 30
1962	28500	27000	Aug. 6	575	Nov. 28
1963	39900	37100	Jul. 18	1330	Jan. 2
1964	49700	47600	Jun. 21	1350	Nov. 25
1965	95300	91600	Jun. 29	1070	Dec. 1
1966		57800	Jul. 6	2280	Dec. 15
1967		51200	Jul. 9	1500	Dec. 7
1968	50769	43580	Aug. 9	1820	Dec. 20
1969		57209	Jun. 18	1097	Nov. 27
1970	93124	80563	Jul. 10	2100	Nov. 8

TABLE 5.2

MAJOR USERS OF THE NORTH SASKATCHEWAN RIVER

(Information supplied by the Alberta Department of Public Health)

Users	Purpose of Use
Town of Rocky mountain house	Water supply & sewage disposal.
Town of Drayton Valley	Water supply & sewage disposal.
Town of Devon	Water supply & sewage disposal.
Imperial oil - Devon	Industrial waste disposal.
City of Edmonton	Water supply, sewage disposal, snow dumping & thermal discharge from power plant.
Edmonton Industries:	
Canadian Industries Ltd. TEXACO Building Products Ltd. S & L oil Ltd., Union Carbide, Gulf Oil canada Ltd., Uniroyal Ltd., Imperial Oil Ltd. McColl Frontenac Oil Co. British American Oil Co. Chemcell Ltd.	Water supply and Industrial waste disposal.
County of Strathcona	Municipal Sewage disposal.
City of Edmonton Lagoons:	
Alberta Hospital - Oliver Sherwood park Edmonton meat packing plants.	Domestic & Industrial Waste storage for disposal in summer months.
Town of Fort saskatchewan	Municipal sewage disposal
Sherritt Gordon Mines Ltd. Dow Chemical Ltd.	Water supply and waste water disposal.

(cont. TABLE 5.2)

Users	Purpose of Use
Town of Redwater	Water supply and waste water disposal.
Imperial Oil - Redwater	Industrial waste disposal.
Western Chemicals Ltd. Duverney.	Water supply and Waste water disposal.
Town of Elk Point	water supply and waste water disposal.
Canadian salt Co. Ltd. Lindberg.	Water supply and waste water disposal.

5.3 Preparation for Simulation

The river flow simulation requires a long and continuous record of several years of river flow data. Further, the river system under consideration may be stated as follows for dynamic programming convenience.

The first step is to discretize the stream system by dividing it into reaches. The system is consider to be made up of a number of connected segments in which each segment has constant properties. Reach nodes are therefore established at every major waste discharge point or significant change in the system. Significant changes are the tributary flows, changes in flow conditions, etc.

The segment of the river considered in this work is about 200 miles long. This segment is divided into 24 (N) reaches as shown in Figure 5.4. The i^{th} reach stretches from t_{i-1} to t_i. The time of travel in each reach depends on the velocity and other hydraulic constants. The time or the length of a recah is equal to $(t_{i-1} - t_i) = X_i$ days, time expressed in length. Assume that aerators $A_0, A_1, A_2, \ldots\ldots, A_{N-1}$ are located at $0, 1, 2, \ldots\ldots, N-1$, the top of each of N reaches. For simplicity the capacity of these aerators are assumed to be equal to the increment in the level of DO needed at those points, they are V_1, $V_2, \ldots\ldots, V_N$.

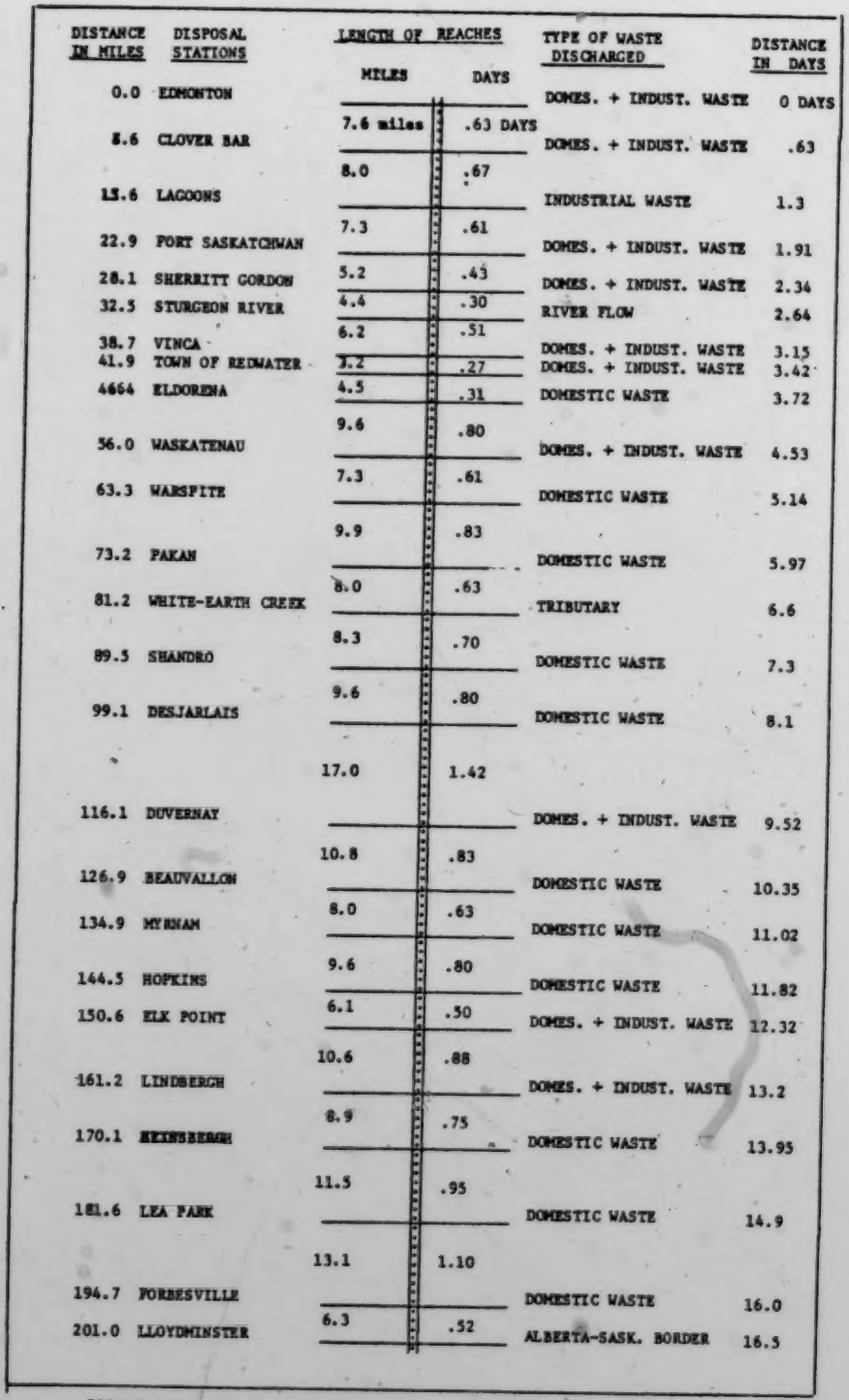


FIGURE 5.4: Schematic Illustrating the North Saskatchewan River Division of Reaches, Length of Reaches, Type of Waste Discharged, Distance Downstream from Edmonton.

There is no real reason to limit the number of reaches except to meet a constraint on machine storage. The program coding in this simulation model is, for this reason, limited to 24 reaches which should be adequate for most quality control studies.

The next step is the numbering of the reaches. Although an initial computational sequence is included in the model, and numbering may be in any pattern. For dynamic programming application it is most convenient to start numbering at the downstream end and number consecutively. Then, continue numbering upstream on each reach, starting with the downstream most reach, until all reaches are numbered. The numbers should be consecutive, 1, 2, 3, ---- N for N reaches in the system.

The basis for this simulation of the stream flows is an historical record of fifty years daily stream flow data. In the simulation, river flow data are generated in a manner such that the statistical properties of the historical data are preserved. It is desirable to have a long and continuous record of several years of data. The primary source of streamflow data is from the Federal Water Resources Department, Edmonton branch. This data is stored on magnetic tape and is processed further for use in simulation

The model used in this work was developed specifically for generating flows at each stations. The historical data are daily gage records from gaging stations in the river basin, each covering an identical period. The data are checked, missing data are filled and monthly averages are computed by an auxiliary program called CHKDATA (Appendix-A).

The transformed historical monthly gage data are analyzed statistically to determine the mean and standard deviation. This mean and standard deviation computed from historical data for waste disposal station i is used to simulate the rate of waste flow into the system at stage i (i = 1, 2, ------, N=24). The river flows and waste flows from each stations were generated by making a linear transformation. The objective is to maintain the statistical appearance of the historical data in generating the synthetic data.

5.4 Simulation Model Operation

The simulation model is actually two simulation models. The first model, CHKDATA, is designed to read daily raw streamflow data. It then computes monthly averages for each reach. The monthly averages computed by CHKDATA will be an input to the second model, RIPSIM. This model simulates the riverflow and quantity of waste discharged at each reach. Then it calls the subroutine OPTMOD, to optimize the amount of aeration required at the top of ecah reach to maintain water quality. The two programs can be run operated together requires considerable computer capacity (42500 bytes). Generally, it is convenient to run the CHKDATA separately, storing the output on magnetic tape (or disk). This output then becomes input to the simulation program.

The simulation program requires inputs of gage data; reach designations, location, length of each reach, initial BOD and DO deficit, minimum DO value and the rate of waste flow into each reach. The program establishes the computational sequence and sets up the weight matrix by computing the aeration cost for the discretized DO values. Simulation begins at the downstream end and proceeds, reach by reach, upstream, computing the BOD concentrations, DO deficit, at the upstream and downstream ends of each reach and checks for a deficit stationary point within the reach under consideration. The maximum value of the deficit in

that reach is subtracted from the DO saturation value (Cs) to obtain the minimum DO concentration, which is compared to the standard. A value less than the standard results in an indicated violation. The program outputs the violation DO value, reach number and the time, the violation occured. To avoid this violation the optimization program, OPTMOD, compute the amount of aeration required at the top of that reach.

In the actual program constraint (4.19) was checked at each stage by two IF statements to force the aeration capacity V(i,j,k)[5] to satisfy the constraint (4.19) in the following ways:

If V(i,j,k) was larger than Cs, then set it equal to Cs, if it is less than zero, then a very large cost is assigned. This negative aeration capacity will definitely not constitute an optimal policy due to its very large cost. Constraint (4.18) can be relaxed by defining a feasible region for the state variable (0 to 9mg/l). In this feasible region, the state variable will be discretized into M (M=11) values with Cs as its maximum and zero as its minimum value.

---

[5] Defined in Appendix-A, section A2.4 'Dictionary of Variables'.

To start the algorithm, the number of aerators are assumed to be equal to the number of stages N. At each stage a decision regarding the amount of aeration must be made. The amount of aeration vary from 0 to 9mg/l in this case.

At any stage i each one of the M discretized states D(i,k) is coming from any one of the M discretized states D(i-1,j) of stage i-1 by a corresponding aeration with capacity V(i,j,k) to each K and subsequently there are M total cost values Z(i,j,k) for each K. Among the M cost values for a particular K*, the minimum cost and the state position j* which gives the minimum total cost for this particular K* are stored. We store such M minimum cost values corresponding to K* = 1, 2, 3, ------, M at stage i. At the final stage N, we pick up the minimum of those M minimum cost values from a particular position *K (K* and *K are different, where *K is the minimum of K* values) which is the minimum total cost of the whole system.

By tracing forward the corresponding state positions which eventually give the final state position *K at every next stage. This gives the optimal policy for that selected ϵ value. If this optimal policy satisfy the constraint (4.17), then it is the optimal policy for the original problem, equations (4.12) and (4.16) to (4.19). If not, the value of ϵ is modified and the whole procedure is repeated.

A new unconstrained minimization system, equations (4.20) to (4.22) is formed whenever a new nonnegative ϵ is used. If an unconstrained minimum of this new system can be found to be Z* and the total aeration capacity used in achieving this optimal solution to be Y*, then by the Everett's theorem (Everett III 1963) this solution is a solution to the original problem, equations (4.12) and (4.16) to (4.19), except Y* is used instead of Y in equation (4.17). Hence by sweeping through a set of ϵ values to solve a spectrum of problems, total available aeration capacities and their corresponding optimal policies are produced in the course of solution.

Instead of assigning a fixed value to the total available aeration capacity Y, 17 different values for ϵ were assigned over the range between zero and one hundred and then solved each of the 17 unconstrained problems.

The entire process can be considered as a learning device. Each value of ϵ yields a certain amount of information about the system response. This information is considered for the feedback to the simulator and the simulator generates further action and the cycle is repeated. This process is continued until an acceptable solution is obtained. The existance of optimal value for an objective function is assured by the algorithm, since all possible ways have been evaluated and compared by the

algorithm. For this application, there are 24 stages with 11 discretized states at each stage and the dynamic programming algorithm find the optimum value out of all 11^{24} possible aeration policies in just 1.89 seconds for a given value of weighting factor and Lagrange multiplier.

5.5 Analysis of Results

This study primarily examines a relatively small set of clear management plans, each somewhat flexible to possible changes in future conditions. In terms of dissolved oxygen content, the objective is achieved when the deficit is kept consistently equal to or close to the acceptable limit. Generally, this maximum allowable deficit is prescribed by some regulatory agency. Hence, a system would be called good if the critical deficit continually approached this limit, but never exceeded it. Whenever the water quality goes below the specified limit, then aeration should be provided to keep the water quality above the limit. Now the objective is to minimize the total quantity of aeration supplied to maintain water quality. In this context the results indicates considerable promise for the use of dynamic programming to achieve the specified water quality standard.

The Figure 5.5 and 5.6 are the initial profiles of DO and BOD concentration for different amount of pollution load without artificial aeration. This profiles are obtained by solving equations 4.1 and 4.2 with initial boundary conditions. Figure 5.7 through 5.11 shows a typical optimal aeration capacity allocation policy and the corresponding DO sag profile for the case ϵ equal to 0.1, weighting factors W1 = 0.9 and W2 = 0.1 and for different quantities of

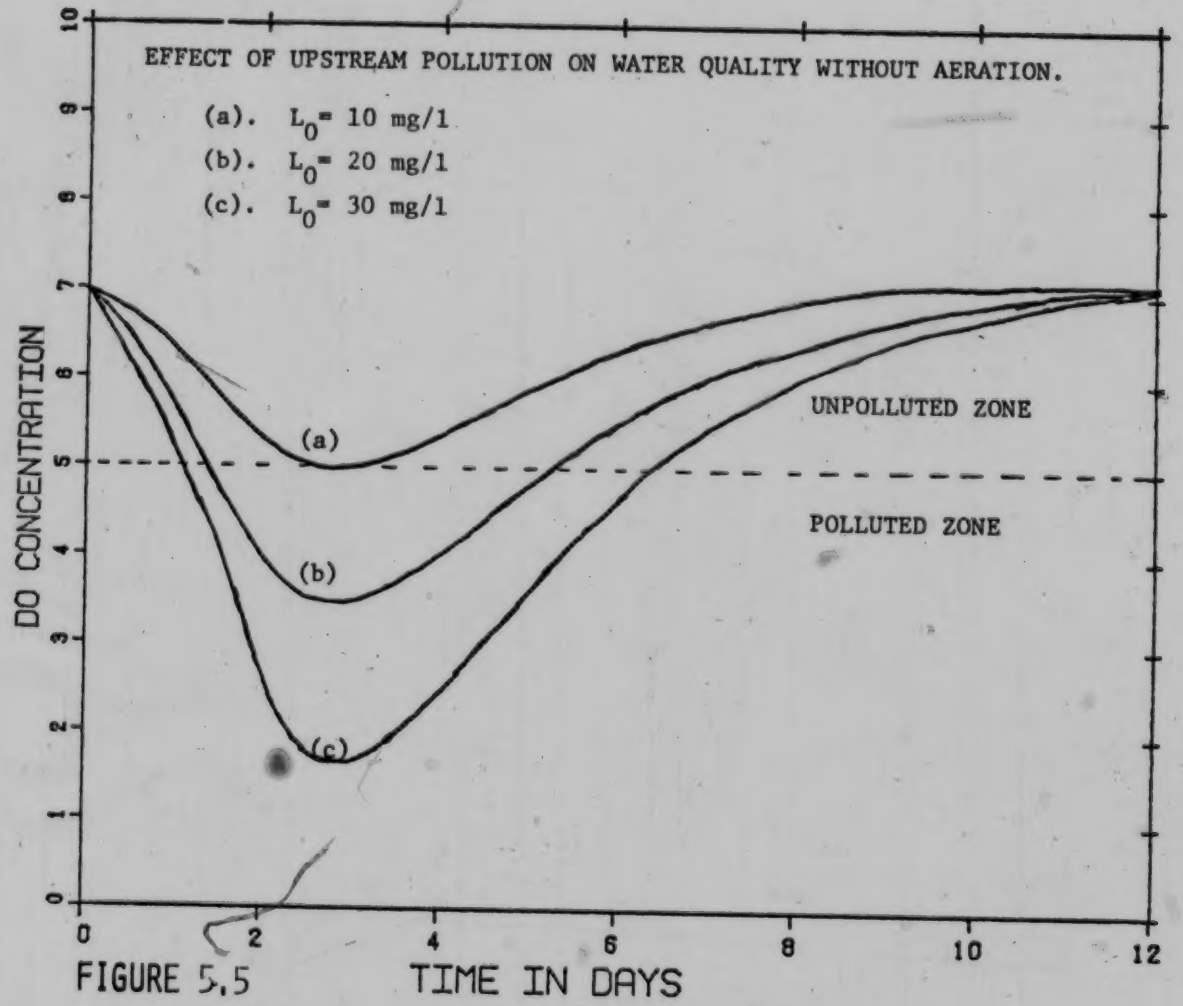


FIGURE 5.5

DO CONCENTRATION WITHOUT WASTE FLOW AT REACHES

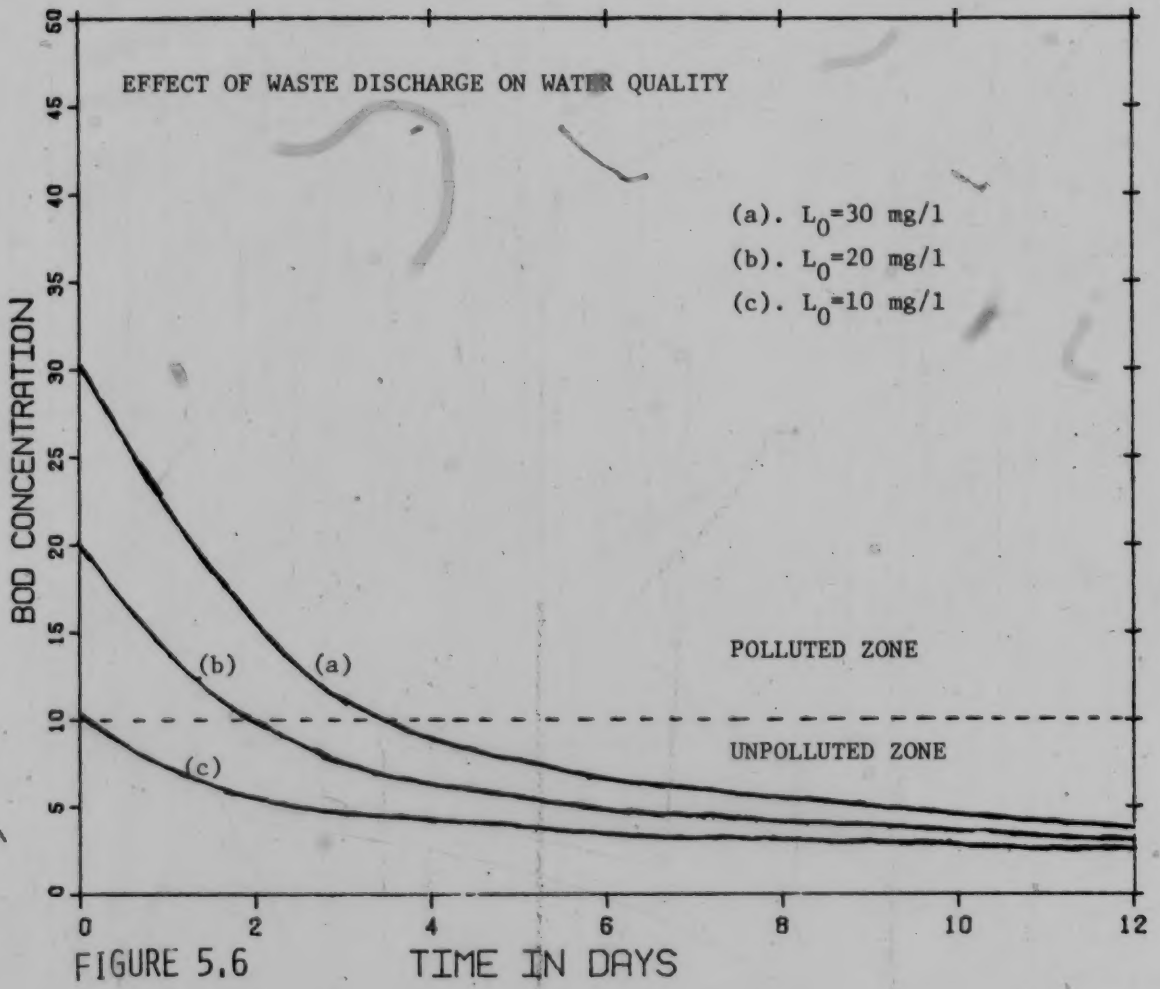


FIGURE 5.6 BOD CONCENTRATION WITHOUT WASTE FLOW AT REACHES

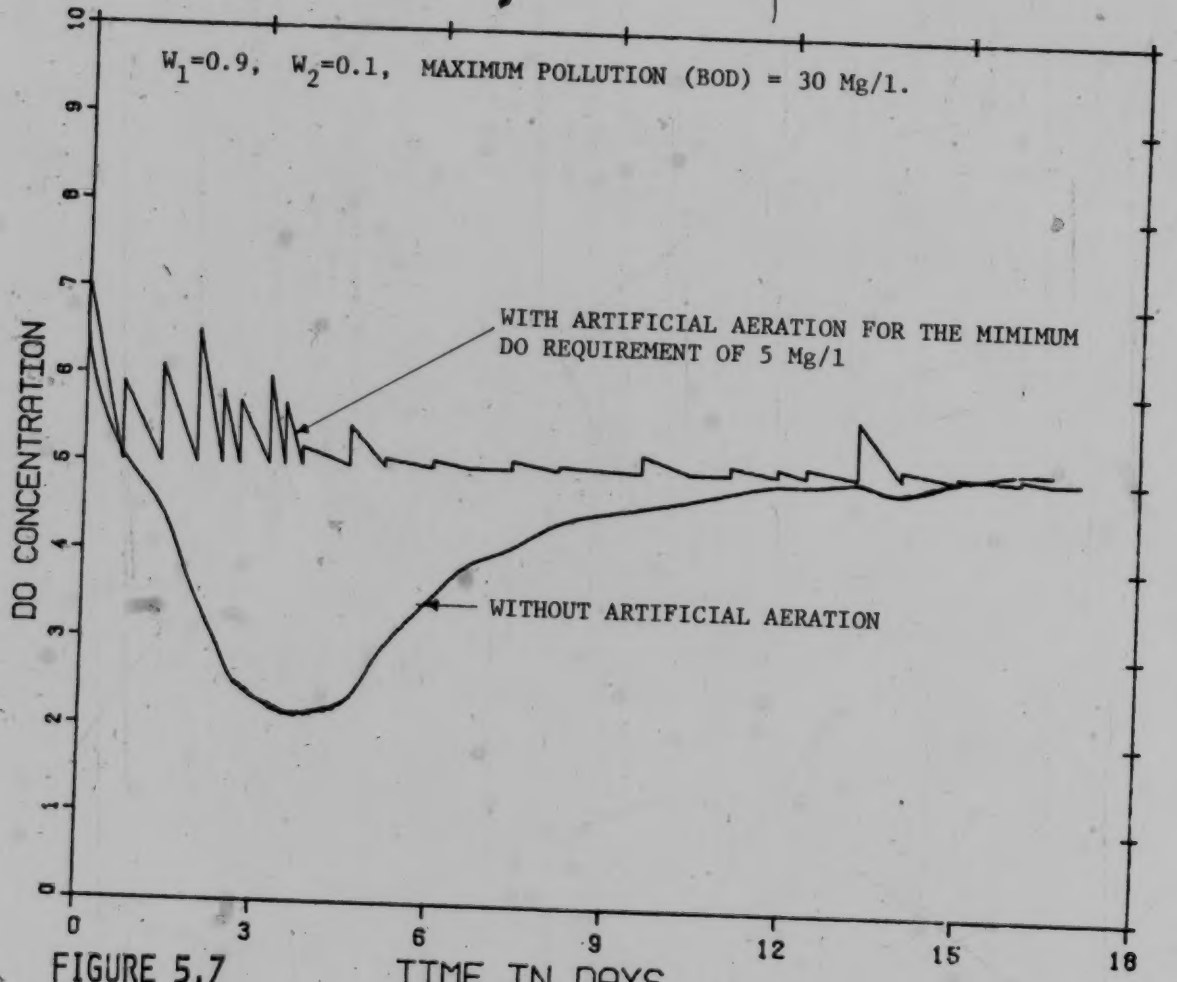


FIGURE 5.7 AERATION CAPACITY AND DO SAG PROFILE

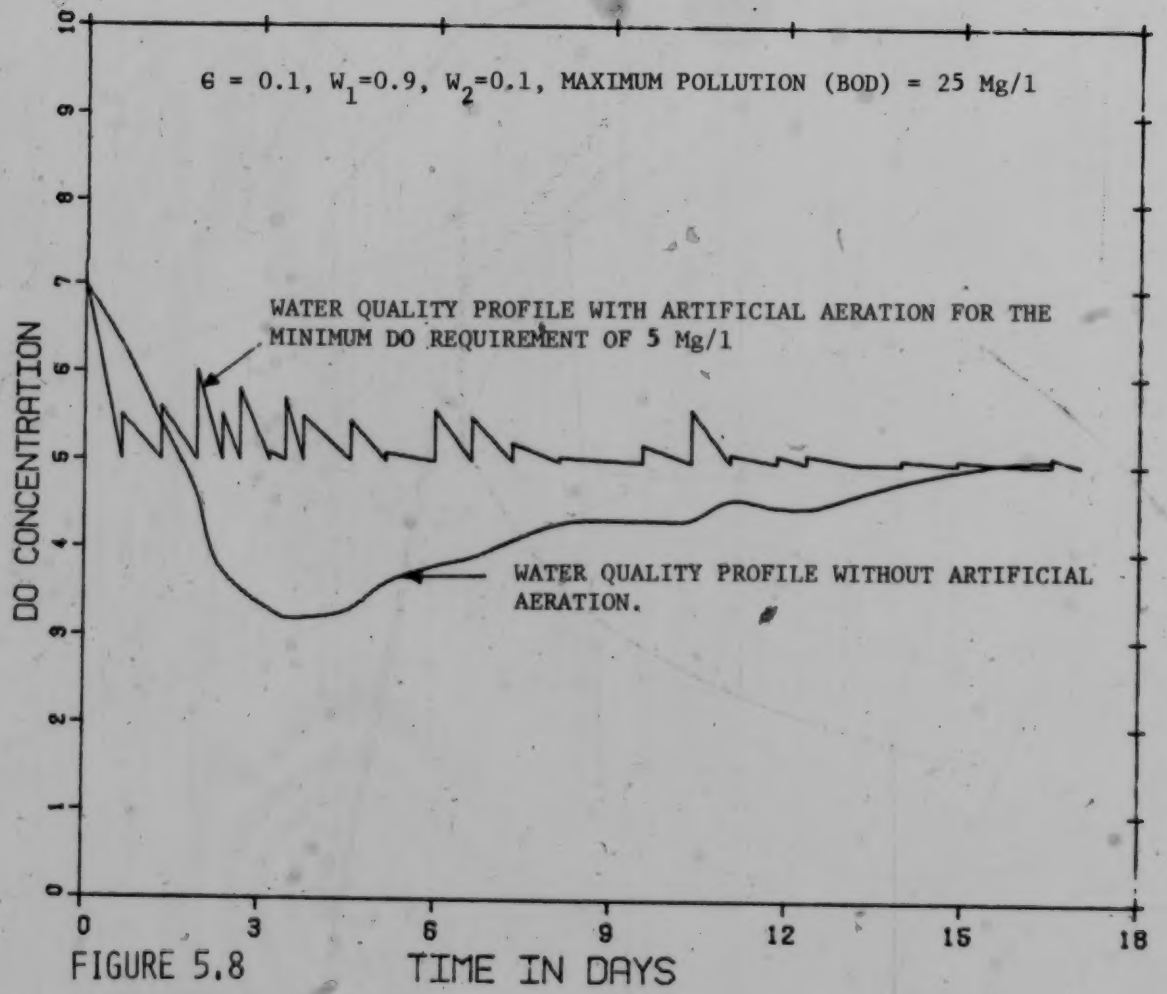


FIGURE 5.8

AERATION CAPACITY AND DO SAG PROFILE

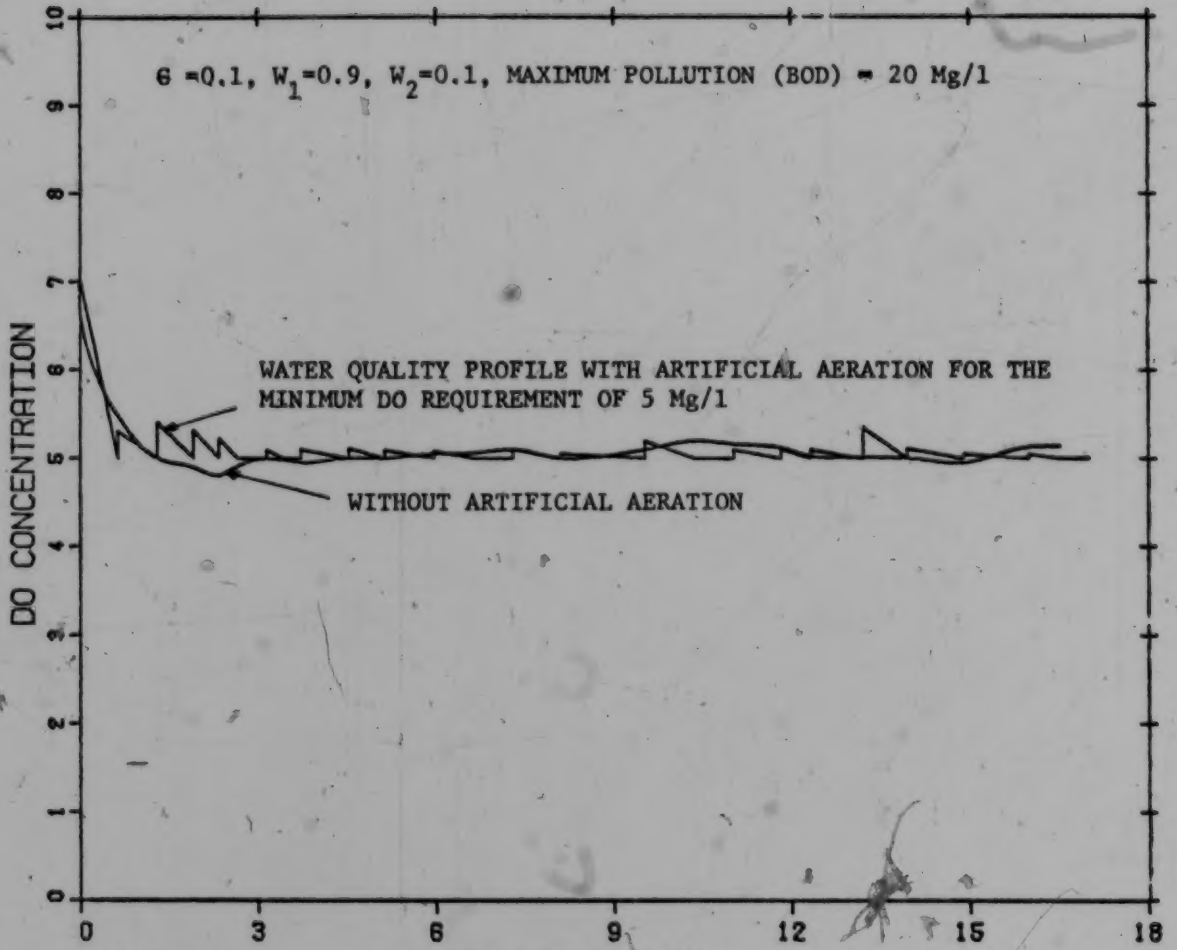


FIGURE 5.9 AERATION CAPACITY AND DO SAG PROFILE

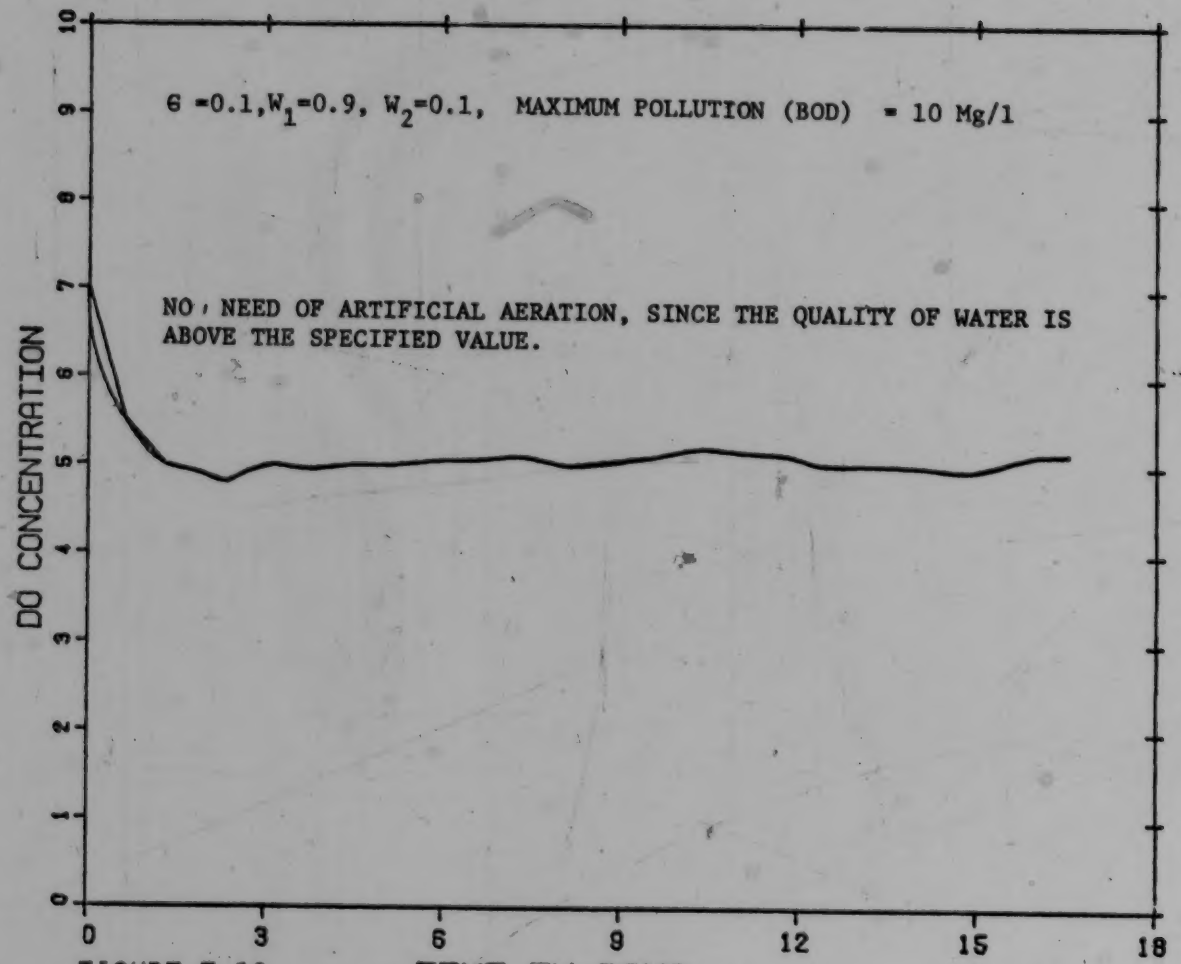


FIGURE 5.10 AERATION CAPACITY AND DO SAG PROFILE

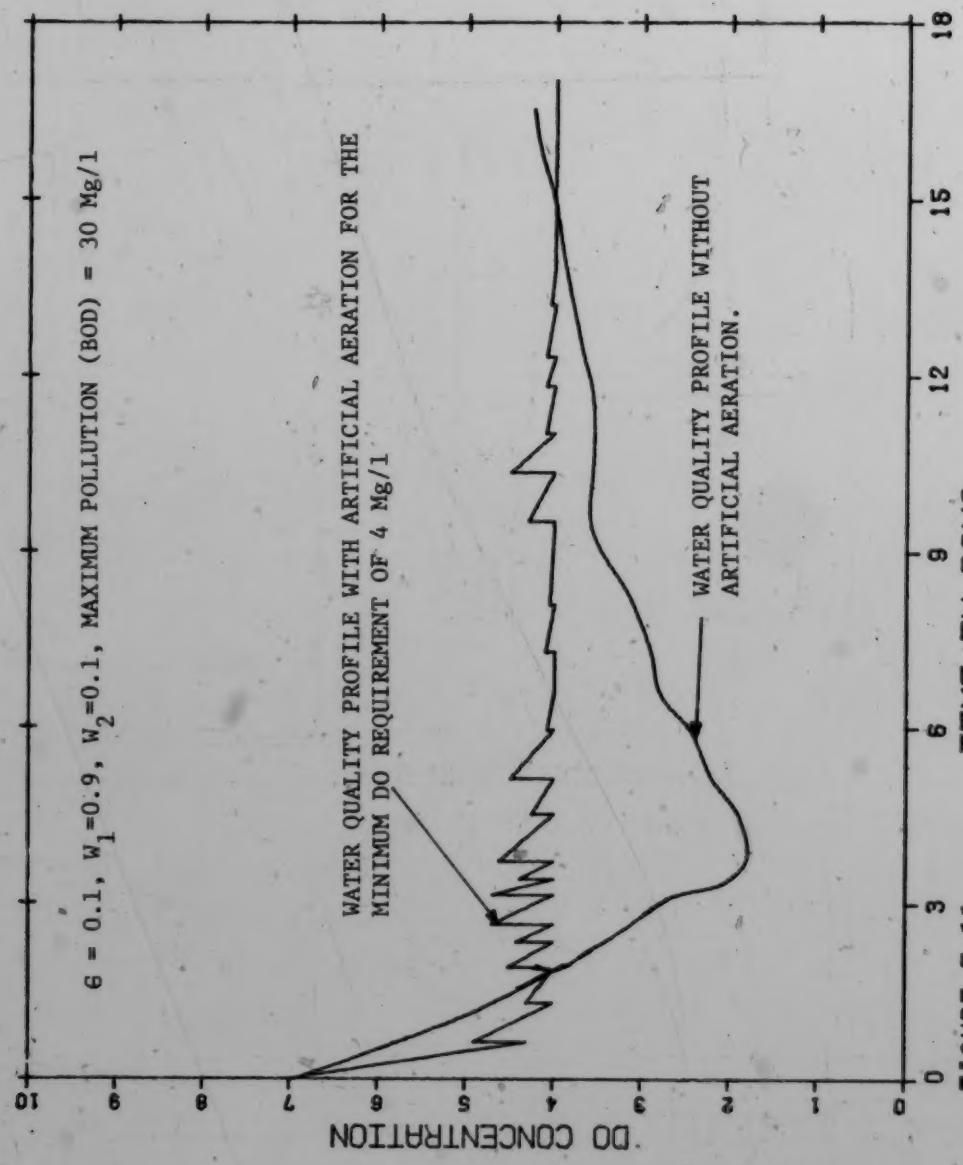


FIGURE 5.11 AERATION CAPACITY AND DO SAG PROFILE

pollution load. The solid line gives the DO sag profile without artificial aeration.

In order to show the effects of various weighting factors on the optimal policy, the following five sets of weighting factors have been tested to each of 17 different values of ϵ.

$$(W1,W2) = (.9,.1),\ (.7,.3),\ (.5,.5),\ (.3,.7),\ (.1,.9)$$

Figure 5.7 shows a typical optimal aeration capacity allocation policy and the corresponding DO sag profile for the case of ϵ equal to 0.1 and weighting factors W1 = 0.9 and W2 = 0.1. In Figure 5.7 the solid line gives the DO sag profile without using artificial aeration. The total available aeration capacities corresponding to different values of ϵ and weighting factors are given in TABLE 5.3. By using the results of TABLE 5.3, Figure 5.12 was plotted to illustrate the typical relationship between the total available aeration capacity and different values of ϵ.

As mentioned before, the main concern of the dynamic programming approach, therefore, is to show how artificial instream aeration can be optimized so as to minimize the relative cost of design and operation for several competing design criteria. With this in view the following results were observed.

TABLE 5.3. The Total Available Aeration Capacities Corresponding to Different Values of e and Weighting Factors

e	W1=0.9	W1=0.7	W1=0.5	W1=0.3	W1=0.1
100	5.76	5.76	5.76	5.76	5.76
12	5.76	5.76	5.76	5.76	5.76
10	5.76	5.76	5.76	5.76	5.76
8	5.76	5.76	5.76	5.76	5.76
6	5.76	5.76	5.76	5.76	5.76
4	5.76	5.76	5.76	5.76	5.76
2	6.45	6.12	5.78	5.78	5.78
1	6.73	6.46	6.26	5.78	5.78
0.8	6.75	6.62	6.33	5.85	5.78
0.6	6.95	6.73	6.46	5.97	5.78
0.4	7.17	6.97	6.48	6.12	5.78
0.2	7.35	7.08	6.86	6.28	5.78
0.1	7.35	7.15	6.99	6.31	5.79
0.01	7.35	7.22	7.04	6.59	5.83
0.001	7.35	7.22	7.06	6.61	5.83
0.0001	7.35	7.22	7.06	6.61	5.83
0.0	7.35	7.22	7.06	6.61	5.83

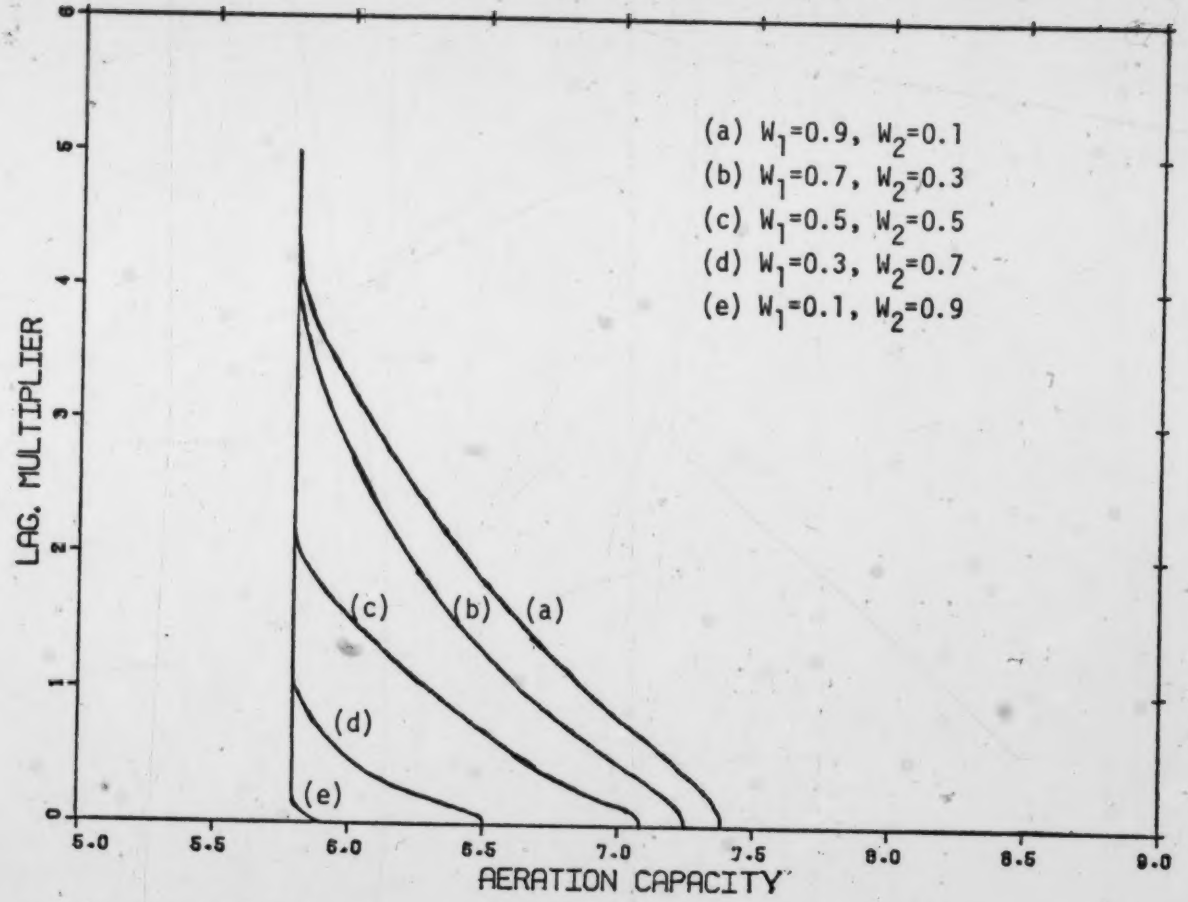


FIGURE 5.12: PARAMETRIC CURVE FOR AVAILABLE AERATION CAPACITY

1. The amount of aeration required to maintain the specified water quality standard increases with increasing waste discharge (Figures 5.7 to 5.11). For a stream with a BOD concentration of less than 10 mg/l, the DO content of the whole stream remains above 5 mg/l and thus no aeration is required (Figure 5.10). However, if the BOD level is raised beyond 20 mg/l, artificical aeration is needed (Figures 5.7, 5.8, 5.9 and 5.11) .

2. Since W1 and W2 are relative weighting factors, the cost function Z constitute a relative cost in optimization. The dimension of Z is 'dollars' or dimensionless, depending on how one interprets W1 and W2. In any event the numeric values of Z computed are proportional to the true cost in optimization.. Further, higher ratio of W1/W2 gives a better DO sag profile in meeting the stream standard for a given value of ϵ, and one can eventually get DO sag profile which is completely below the given stream standard by choosing a very large W1/W2 ratio and a proper ϵ value. DO sag profiles below the stream standard have been observed when ϵ is less than 2 and W1/W2 is set to 9. This shows that the method can be applied to a pollution control problem in which the stream standard is required to be satisfied. In addition, the method can also be used in a preliminary analysis, since by

varying the values of ϵ, different combinations of the total aeration capacity used and the resulting DO profile can be obtained.

3. The optimal total aeration capacity increases with descreasing ϵ value. This fact is clearly depicted by either Figure 5.12 or TABLE 5.3. As stated before the lagrange multiplier ϵ has the meaning of price, large value of ϵ means a higher cost for allocating an unit aeration capacity into the system. The amount of total aeration capacity will increase with value of ϵ goes down (Figure 5.12). The rate of increase will decrease gradually. The maximum capacity is attained when ϵ equals to zero. This is the limiting case in which there is no limitation on the total available aeration capacity.

4. The optimal total aeration capacity decreases with the increasing weighting factor W2, this implies that if the aeration costs are weighted more and more heavily, the total available aeration capacity will decreases. This fact can be observed from TABLE 5.3.

5. There exists a certain range for the total available aeration capacity with respect to the change of ϵ, beyond this range, any change in ϵ, will not affect the amount of total resource. A near optimal policy

can be obtained within the gap by an approximation technique (Everett III 1963). Figure 5.12 demonstrate that the range begins approximately when ϵ becomes greater than four.

CHAPTER SIX

CONCLUSION

One of the problems in river pollution control is to find an acceptable condition-cost relation so that agreement can be reached and the necessary control established. In this paper an attempt is made to build a model of the system which reveal certain salient features of the system. The main demand is for interaction between water pollution engineer and the computer, so that the engineer may maintain overall control and evaluate the system over intermediate results to modify the parameters if he desires.

The method of analysis presented herein is a significant departure from the traditional methods for river pollution control. In current practice, it is customary to go for either a low flow augmentation dams or the enhanced in-plant treatment. The enhanced in-plant treatment is widely used nowadays; however, its inflexibility and its relatively high cost do not necessarily make it the best method for waste abatement. The low-flow augmentation reservoir is expensive and further, it is not possible in certain situations. Artificial aeration, though still in the stage of development, offers many special advantages.

The use of lagrange multiplier in the solution of

allocating limited resources allows the original constrainted optimization problem to be simplified to an unconstrained one. In general, different values of ϵ lead to different total available aeration capacities, hence one can find all possible available capacities and its corresponding optimal allocation policy by changing the value of ϵ successively over a wide range. Then a parametric curve for the total available aeration capacity with respect to ϵ can be plotted for a given range of pollution value. Once a total aeration capacity is selected based on the budget, one can find the corresponding ϵ value using Figure 5.12. By utilizing this value of ϵ in the modified system, equations 4.16 to 4.19, one can find the optimal allocation policy for the given aeration capacity by solving the discretized dynamic programming algorithm.

The use of a dynamic programming algorithm in this nonlinear optimization problem is very efficient in obtaining the optimal policy for the given aeration capacity. Computational effort is the limiting factor in the size of the problem that can be handled, that is, the number of discretized states chosen depends on the computer time and storage available. Most of the computational effort is involved in the evaluation of objective function. For a given number of stages(N) the number of times the objective function to be solved is directly proportional to the number of states in each stages. That is, doubling the

number of states will approximately double the computational effort. In this example there were 24 stages with 11 discretized states at each stage and the dynamic programming algorithm find the optimum value out of all 11^{24} possible aeration policies in just 1.89 seconds for a given value of weighting factors and lagrange multiplier.

The existance of optimal value for on objective function of the discretized type variable is assumed by the algorithm itself, since all possible ways have been evaluted and compared by the algorithm. Philosophically speaking, it is generally impracticable to implement the entire optimal solution in practice; in fact it is seldom necessary to do this. This optimal control solution can serve a very useful purpose, however, in establishing limits of performance and relative cost. It is perhaps even more useful in comparing the optimal design policy with several competing suboptimal designs.

The model described in this work is limited to those needed to demonstrate the general utility of dynamic programming approach to river pollution control. Due to the comprehensive nature of the model and its flexible procedures, many other input-output studies are possible. The model is inherently quite flexible, and any or all of the relationships may be modified without changing the dynamic programming methodology.

It is emphasized that the choosen relationships are not necessarily the best for every day and every season. But the concept of dynamic programming approach for the control of river pollution is most significant in this paper. Methodology such as the one the author has developed is useful for the present, only at an elementary stage. Much research is needed before its use could become practicable.

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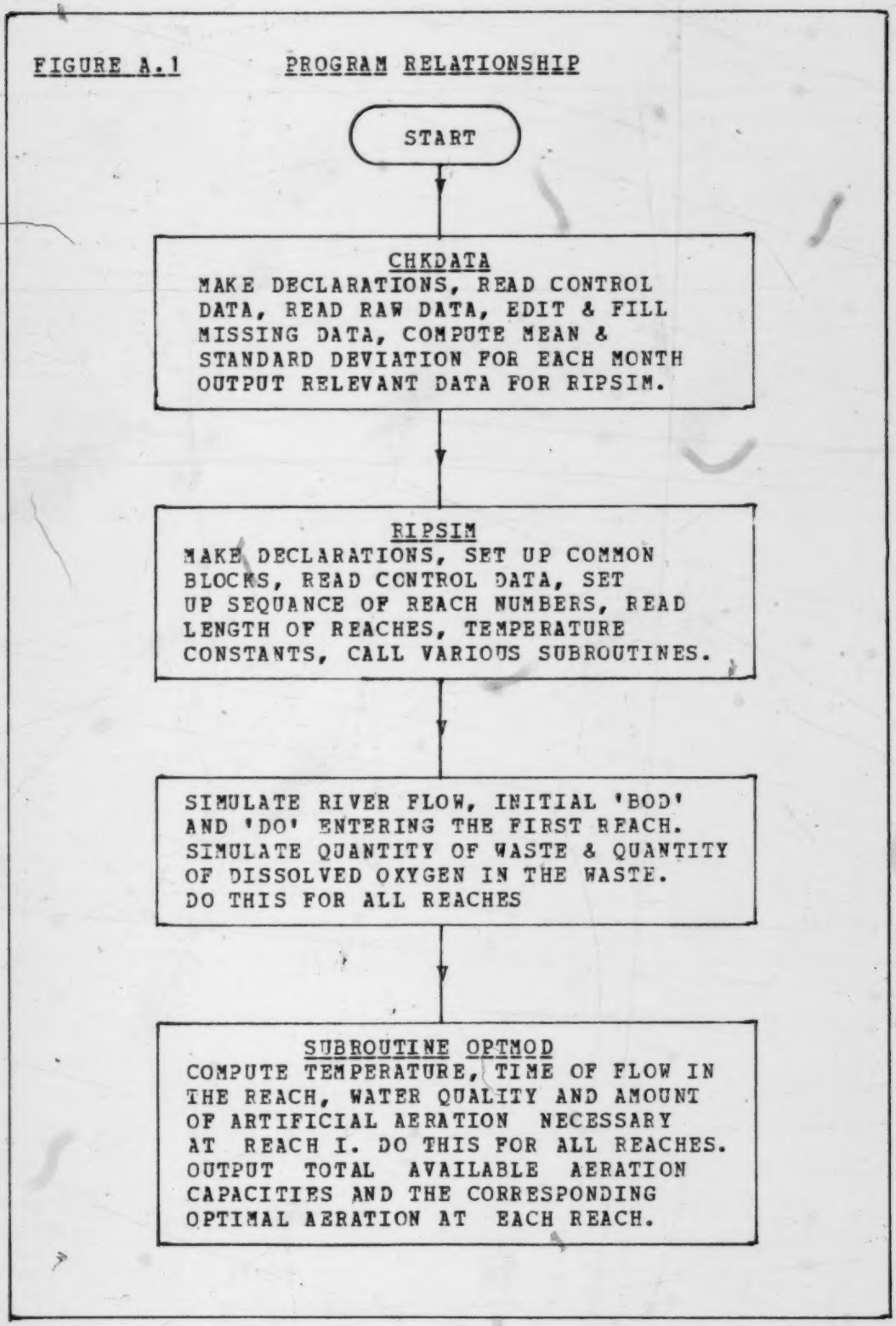
APPENDIX-A

USER'S MANUAL

The material contained in this appendix is intended for those making the detailed preparation for the use of CHKDATA, RIPSIM (RIver Pollution SImulation Model) and OPTMOD (OPTmization MODel). This appendix has been prepared in sufficient detail to serve as a manual for guidance in the preparation of program inputs and control statements. The information is separated into program components and each component is described in the following pages.

FIGURE A.1 PROGRAM RELATIONSHIP


START
CHKDATA
MAKE DECLARATIONS, READ CONTROL DATA, READ RAW DATA, EDIT & FILL MISSING DATA, COMPUTE MEAN & STANDARD DEVIATION FOR EACH MONTH OUTPUT RELEVANT DATA FOR RIPSIM.
RIPSIM
MAKE DECLARATIONS, SET UP COMMON BLOCKS, READ CONTROL DATA, SET UP SEQUANCE OF REACH NUMBERS, READ LENGTH OF REACHES, TEMPERATURE CONSTANTS, CALL VARIOUS SUBROUTINES.
SIMULATE RIVER FLOW, INITIAL 'BOD' AND 'DO' ENTERING THE FIRST REACH. SIMULATE QUANTITY OF WASTE & QUANTITY OF DISSOLVED OXYGEN IN THE WASTE. DO THIS FOR ALL REACHES
SUBROUTINE OPTMOD
COMPUTE TEMPERATURE, TIME OF FLOW IN THE REACH, WATER QUALITY AND AMOUNT OF ARTIFICIAL AERATION NECESSARY AT REACH I. DO THIS FOR ALL REACHES. OUTPUT TOTAL AVAILABLE AERATION CAPACITIES AND THE CORRESPONDING OPTIMAL AERATION AT EACH REACH.

A1.1 CHKDATA - Stream Flow Data Edit Program

Purpose: The CHKDATA program is designed to read daily raw streamflow data of the type available from the Federal Water Resources Branch, Edmonton, Alberta, for their stream gaging stations and to prepare these data for use in synthetic streamflow data generator. The program reads the raw data from magnetic tape, checking as it does so to ensure that the data being read are in the proper sequence, for the proper station and for the years of record desired.

When all desired raw data for one month have been read in the proper order, the program searches for missing data. If more than one month of consecutive data are missing, the program calls exit and the operator must reschedule the data sequence to remove that period from use. If fewer than one month of data are missing, the program fills the missing data so that the output is a complete set of daily streamflow records.

Missing data are filled by noting the day of the month and year of the missing data item and its station number. Then a mean of all other days of that month data item corresponding to the one which is missing is computed. The mean of mean and standard deviation for that month are computed from these data items and then the missing item is computed according to the formula:

$$Q(i) = mean(i) + std(i) * r(i)$$

Where

Q(i)	=	the computed missing data item.
mean(i)	=	the mean of all data available corresponding to that month.
std(i)	=	the standard deviation of all data available corresponding to the month and station of the missing data item.
r(i)	=	a standard normal random deviate.

Having read, edited and filled the missing data, the program then computes and outputs the mean flow and standard deviation for that month. There are 12 means and 12 standard deviations for each station. These means and standard deviations are used in the synthetic data generator.

A1.2 Program Components

The CHKDATA program consists of the subroutines, listed with their lengths in bytes, as follows:

CHKDATA MAIN ----- 10510		AVM ---- 706
INPUT ----- 1288		RAN ---- 832
INCARD ----- 1640		RANDU -- 448
FILL ----- 1332		

CHKDATA MAIN

This program component reads the program contolling information, coordinates the work of the other subroutines, makes certain checks and outputs the edited data. The program controlling information is supplied on two cards (explained in Program Input and Output section). The controlling information establishes the waste disposal points, the year in which data for each point begin and end.

After identifying the points, the subroutines INPUT and INCARD are called. These subroutines read the data one month at a time, perform certain checks described below, and return for one month to CHKDATA MAIN. Checks for the station number and beginning and ending years then are made on the month's data just read. Any deviation from proper order is printed.

When the reading of data is completed, the subroutine FILL is called to fill in missing data. FILL is described below. Finally, depending upon the controlling information supplied, CHKDATA MAIN outputs the edited streamflow data. The data are supplied in printed form, or on magnetic tape. Daily flows are outputed without further change (if required). Monthly flows are the average of the daily flows for one month.

subroutine INPUT

This subroutine transmits the call to read data from CHKDATA MAIN to subroutine ICARD and the data read back to CHKDATA MAIN. Before the data are sent to CHKDATA MAIN, this subroutine checks to determine that the data read are of proper station, month and year. The data are tramsmitted in a one dimensional array, one month's data at a time.

Subroutine ICARD

ICARD actually reads the supplied raw historical data. The subroutine checks to determine if the data are in the proper monthly sequence. Data for one month at a time are read, checked, and transmitted to subroutine INPUT.

Subroutine FILL

After the data are all read and checked, subroutine fill is called to determine if there are any missing data points. If thirty or more consecutive daily data points are missing

for any station, exit is called and the operator must make an adjustment in the data years used. If scattered data points are missing, the subroutine fills the missing points one at a time, as described above.

Subroutine RAN and RANDU

These subroutines generate standard normal deviates (mean=0, and variance=1) for use in subroutine FILL.

Subroutine AVM

Subroutine AVM compute the monthly average flows from the edited and filled daily data and outputs on a magnetic tape, disk or cards, depending on the control number entered for the variable ITAPE.

A1.3 Program Input Format

Input format and the meaning of certain important variables are as follows:

CHKDATA MAIN

Card #1 FORMAT(9I5)

IYR1(I) = The starting year for station (I).

IYR2(I) = The ending year for station (I).

NNSTA = The number of disposal points.

ITAPE = 4 for data input on tape.

= 5 for data input on cards.

ISTART = A starting random number.

ITIME = 1 for daily flow output.

= 2 for average monthly flow output.

IPRINT = 0 if output is not to be printed.

= 1 if output is to be printed.

NTAPE = 0 if output is not to be taped

= 1 if output is to be taped.

Card # 2 FORMAT(10I8) (ISTA(I) , I= 1, NNSTA)

Indicates the station number for which data are to be read. These station numbers must correspond to the reach numbers. The number of stations, NNSTA, may be fewer than the number of reaches but the order in which stations are read must be the same as the reach numbers.

Subroutine ICARD

A set of input streamflow data cards are required to input all stream flow data. The data format is:

FORMAT(I8,I4,I2,8F6.2)

where,

I8 = the station number.

I4 = the calender year.

I2 = an Index, 1, 2, 3, or 4, which identifies the number of the card in the month.

8F6.2 = The daily streamflow values for 8 consecutive days. The first card contains flow data for the first 8 days, the second for the 9th through the 16th day, the third for the 17th through the 24th day and the fourth for the 25th day through the last day of the month, 28,29,30 or 31, as appropriate.

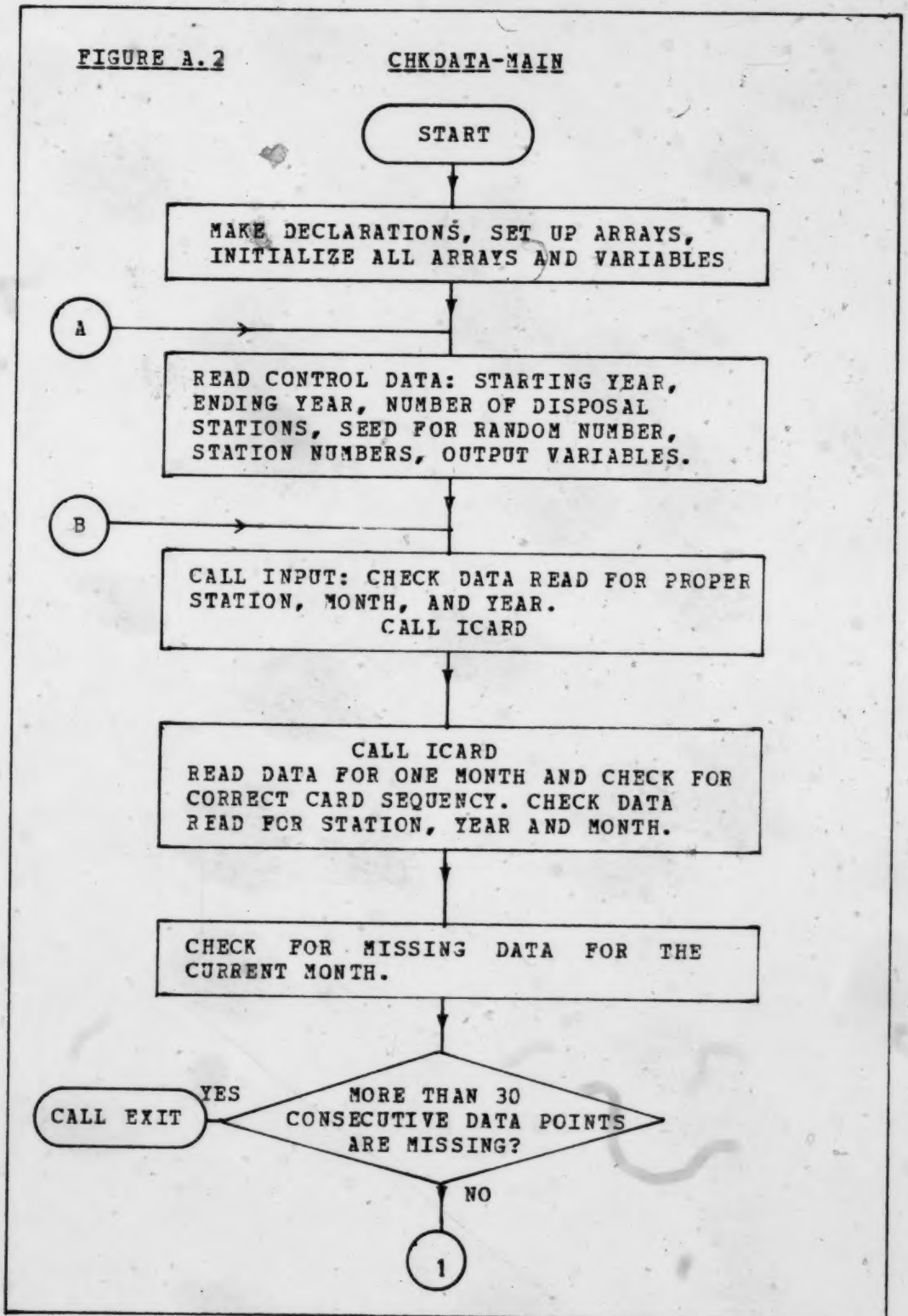
A1.4 Dictionary of Variables.

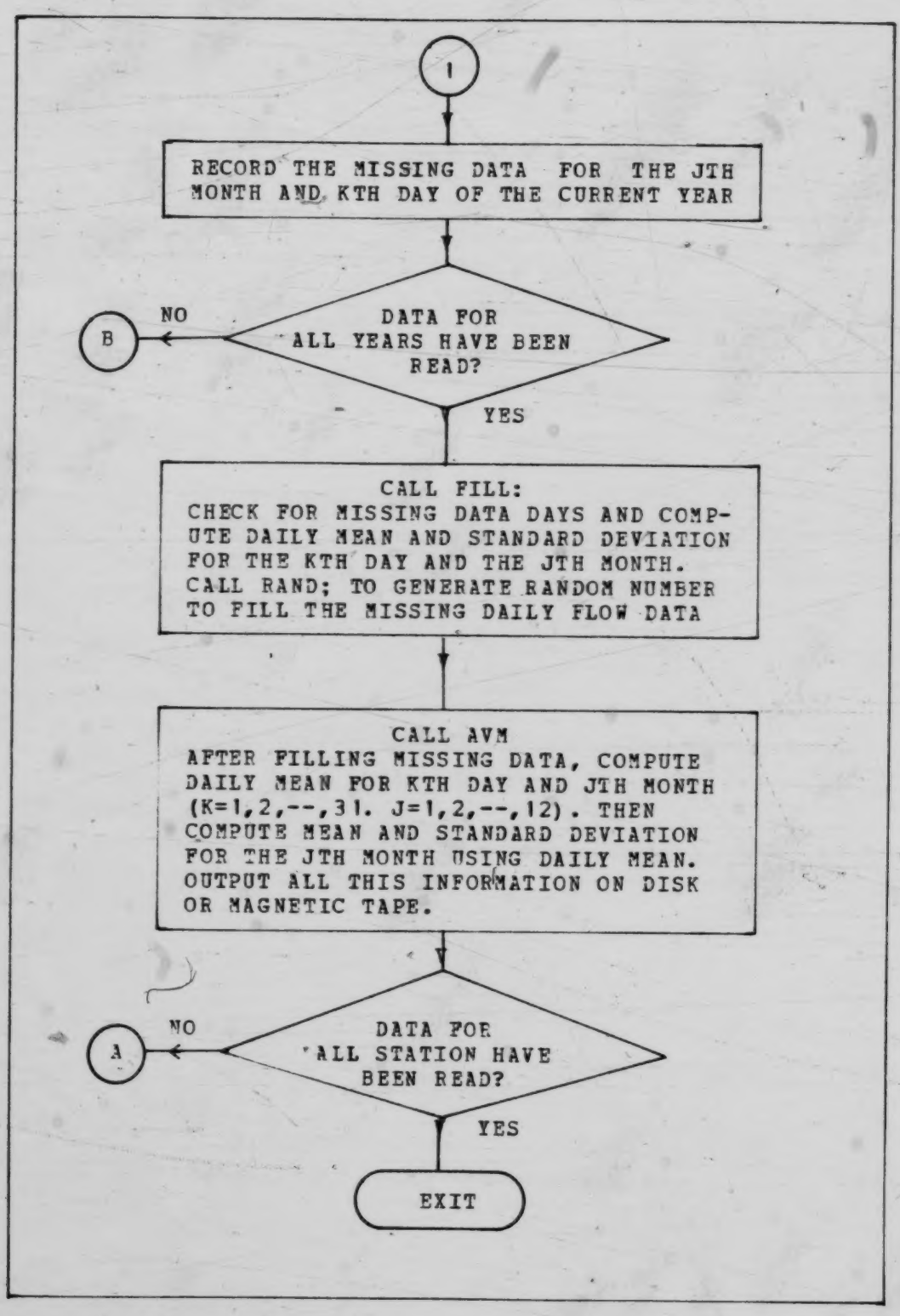
Following is a list of variables used in CHKDATA and their meanings in brief:

AV2(I,J)	Average flow during Ith month of the Jth year
FN	Number of data items.
ICARD(I)	Card sequence number.
ICOUNT	Convenience Index.
IDAY	Day counting variable
IISTA	Convenience station number, for checking.
IIYRI	Convenience starting year, for checking.
IIYR2	convenience final year, for checking.
IPUNCH	Control variable-output.
ISTART	Starting random number.
ISTA(I)	Identifying number, Ith station.
ITAPE	Control variable for output, =4 data on tape =5 data on cards =6 data on disk file
ITIME	Control variable-input, =1 for daily flows. =2 for monthly average flows.
IMONTH	Month counting variable.
IYEAR	Year counting variable.
IYR1(I)	Starting year for data, Ith station.
IYR2(I)	Final year for data, Ith staion.
JPREV	Convenience station number, for checking
JYR	Convenience number of years for checking.
KMO(I)	Identifying number, Ith month.

KSTA(I)	Equals ISTA(I).
KYR(I)	Equals IYR (I).
LMO	Number of months of data, computed.
MONTH	The current month.
ND(I)	Number of days in month I
NEVEN	Convenience number, random number generator.
NMO	Number of months of data counted.
NNSTA	The number of stations.
NNYR	Number of years of data.
WODD	Convenience number, random number generator.
NSTA	Current station number.
NTAPE	Control variable-output, =0 for no data on tape. =1 for data output on tape.
Q(I,J,K)	Gage flow Ith month, Jth day, Kth year.
QMEAN	Mean flow.
QNEW	Computed flow to fill missing data point.
QSTD	Standard deviation of flow.
R1,R2,YFL	Convenience variables, random number generator.
RN(I)	Random number, Ith time frame.
SUM	Sum of second term.
S(I,J)	Flow for Jth day of Ith month.
Z(I)	Temporary storage, flow on Ith day in current month.
Z(L)	Temporary linear storage for one month's flow.

FIGURE A.2 CHKDATA-MAIN


START
MAKE DECLARATIONS, SET UP ARRAYS, INITIALIZE ALL ARRAYS AND VARIABLES
A
READ CONTROL DATA: STARTING YEAR, ENDING YEAR, NUMBER OF DISPOSAL STATIONS, SEED FOR RANDOM NUMBER, STATION NUMBERS, OUTPUT VARIABLES.
B
CALL INPUT: CHECK DATA READ FOR PROPER STATION, MONTH, AND YEAR.
CALL ICARD
CALL ICARD
READ DATA FOR ONE MONTH AND CHECK FOR CORRECT CARD SEQUENCY. CHECK DATA READ FOR STATION, YEAR AND MONTH.
CHECK FOR MISSING DATA FOR THE CURRENT MONTH.
MORE THAN 30 CONSECUTIVE DATA POINTS ARE MISSING?
YES
CALL EXIT
NO
1


1
RECORD THE MISSING DATA FOR THE JTH MONTH AND KTH DAY OF THE CURRENT YEAR
DATA FOR ALL YEARS HAVE BEEN READ?
NO
B
YES
CALL FILL:
CHECK FOR MISSING DATA DAYS AND COMPUTE DAILY MEAN AND STANDARD DEVIATION FOR THE KTH DAY AND THE JTH MONTH. CALL RAND; TO GENERATE RANDOM NUMBER TO FILL THE MISSING DAILY FLOW DATA
CALL AVM
AFTER FILLING MISSING DATA, COMPUTE DAILY MEAN FOR KTH DAY AND JTH MONTH (K=1,2,--,31. J=1,2,--,12). THEN COMPUTE MEAN AND STANDARD DEVIATION FOR THE JTH MONTH USING DAILY MEAN. OUTPUT ALL THIS INFORMATION ON DISK OR MAGNETIC TAPE.
DATA FOR ALL STATION HAVE BEEN READ?
NO
A
YES
EXIT

A2.1 RIPSIM (RIver Pollution SImulation Model)

The simulation program, called RIPSIM, is made up of a controlling program, RIPSIM-MAIN and several subroutines, each of which contributes to the overall program.

A2.2 Program Components.

A list of the subroutines and their length, in bytes are given below.

RIPSIM main	906	TWASTE	522
SIM	1544	TGEN	2772
UPGAGE	1162	TRAN	2852
OPTMOD	15004	IREACH	412
RAN	560	COMPUT	8580
RRN	396	GTRAN	536
STD	490	GFLOW	456

RIPSIM MAIN.

Purpose: The simulation program is controlled by RIPSIM main. This routine sets up ten common blocks needed to transfer variable values from subroutine to subroutine, calls subroutine in the required order and reads the station numbers to be used in simulation. Subroutines TGEN and TRAN are called to set up the reach indices and computation sequence and to compute the reach flow data. The subroutine SIM is called to carry out the simulation process.

Subroutine SIM

Subroutine SIM reads in constants and data needed to compute the temperature and waste parameter values for each reach, computes the deterministic component of the temperature equation, and through two independent "do loops" to perform simulation by calling various subroutines. The first of the "do loop" covers from the first reach to N, the number of reaches. This "do loop" also calls RAN which generates the random deviates for the temperature equation.

The second "do loop" computes DO deficit and checks for water quality violation. Inside this "do loop" subroutine QTRAN and OPTMOD are called, successively, to compute flow and the water quality values at each reach. If there is a violation in water quality, the subroutine OPTMOD is called to compute the amount of aeration required to avoid violation. These operations are described below in more detail as individual subroutines. The values of the simulation results are written out within the "do loop". When the simulation is complete, the control will be transfered to RIPSIM main for termination.

Subroutine RAN and RANDU

Subroutines RAN and RANDU are the same random number generating subroutines used in program CHKDATA which have been described previously.

Subroutine GFLOW

Subroutine GFLOW computes total flow at the beginning of reach. GFLOW is called in the first "do loop" to compute total flow in the stream at the beginning for each waste disposal stations being used in the simulation. The computed data are transferred to COMMON/FLOW7 for use by other subroutines.

Subroutine QTRAN.

QTRAN is a short subroutine which receives computed flow data through COMMON/FLOW7 and, convert the computed flow data to stream flow data by linear transformation. The streamflow data are designated QNAT(I), to indicate the flow at the upper end of reach I. These values of QNAT(I) are also entered in COMMON/FLOW7 for use by other subroutines linked through this common block.

Subroutine TWASTE

TWASTE checks whether there is a set of waste load data corresponding to a reach number where a waste discharge is scheduled. If the data are not available for the reach, TWASTE calls RANDU to generate waste load for that particular reach.

Subroutine OPTMOD

After regulated flows in each reach are computed, subroutine OPTMOD is called to compute the water quality values for each reach beginning from the first reach. First, OPTMOD completes the computation of temperature for the time-frame. It should be remembered that OPTMOD is called in "do loop" which is in turn a "do loop". OPTMOD sets up a third "do loop" which cycles over the number of reaches, NR. Thus, for each reach , OPTMOD compute the quality values for each reach before it returns to its calling subroutine, SIM.

The computations are made, starting at the downstream reaches, according to the sequance of computation set by subroutine TGEN..

For each reach, OPTMOD initilizes variables and proceeds to make the computations necessary to evaluate the incoming BOD and DO concentrations, K1 (deoxygenation constant), K2 (reaeration constant) and corrects K1 and K2 for temperature, computes the time of flow in each reach and, finally, the BOD and DO concentrations in water leaving the reach. OPTMOD then checks to determine if the DO deficit has reached a maximum within the reach, in which case the minimum DO concentration will have occured within the reach. This is done by computing TCRIT, the critical time of flow, and comparing it to the time of flow in the reach. If TCRIT < TIME, a minimum DO concentration has occurred in the

reach. TCRIT is then substituted for TIME and the value of DO-OUT is computed and used in turn to compute the minimum DO concentration, XMINDO, in the current reach. If there is any violation, then optimization program, OPTMOD, computes artificial aeration. OPTMOD then writes out the water quality and related values in an array and then returns to its calling routine.

A1.3 Program Input

Data are read into the simulation program, RIPSIM, through RIPSIM main, SIM, GFLOW, and TGEN only.

RIPSIM MAIN

Card #1 FORMAT(2I5)

NYR = the number of times of simulation to be carried out.

NGT = the number of stations for which data are used.

Card #2 FORMAT(2I8)

IGT(I) = the waste disposal station numbers used.

I = 1,...., NGT. Maximum of twenty four.

Subroutine SIM

Card #1 FORMAT(3F8.0, I5, F8.0)

D = constant in temperature equation.

C = lag constant in temperature equation.

TMEAN = mean annual temperature.

ISTART = initial number for random number generator.

SIGMAT = standard deviation of the temperature data.

Card #2 FORMAT(2F10.0, I1)

RLNTH(I) = the length of reach (i), in days.

XK120W(I) = the deoxygenation constant K1 at 20°C for the waste which is introduced into reach I.

IWASTE(I) =1 if there is a waste load introduced in reach I.

=0 if no waste load introduced in reach I.

Card #3 FORMAT(3F10)

QWASTE(I,J) = the rate of discharge of waste in Cfs for reach I and month J.

BODWST(I,J) = the BOD concentration in the waste being discharged into reach I during month J.

DOWST(I,J) = the DO concentration in the waste being discharged into reach I during month J.

Subroutine GFLOW

The computed data are read by GFLOW. The format must be adjusted to the format of the data to be read. Normally, the data will be on magnetic tape . The program as set forth herein reads the data from magnetic tape as QG(I,J), (I=1, NG), (J=1, 12). It reads one year of data for each station.

Subroutine TGEN

Card #1 FORMAT(I5, F10.0)

NR = number of reaches.

NG = number of waste disposal stations.

Card #2 One card for each reach (2I5).

NOR(I) = the reach number, reach I.

FL(I) = length of reach I.

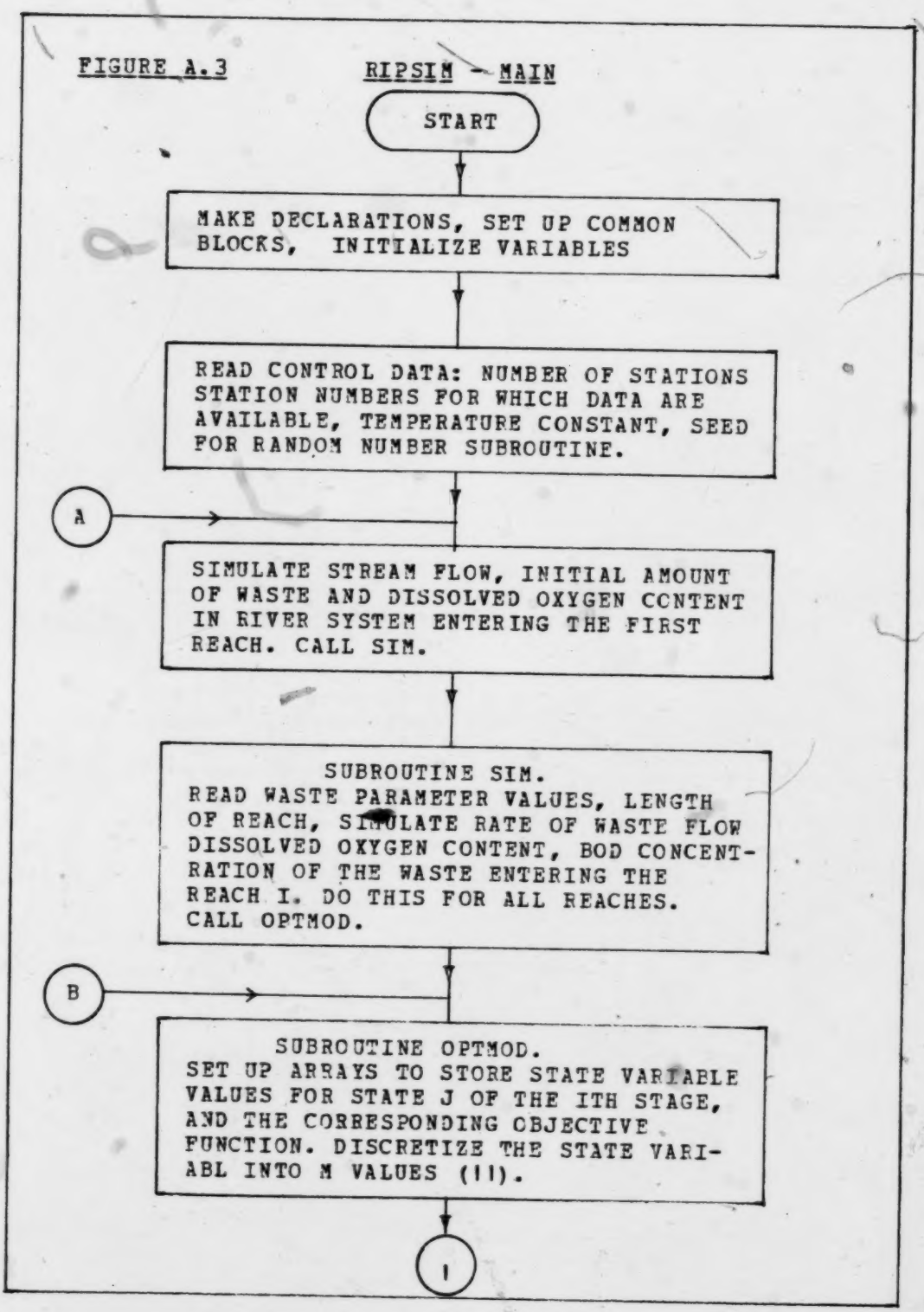
A2.4 Dictionary of Variables

A	Intermediate constant.
AVW(I)	Average waste load, Ith reach (used for periodic load function).
AW(I)	Amplitude of waste load (used for periodic load function.
B	Intermediate constant.
BODIN(I)	BOD concentration at the end of reach I.
BODOUT(I)	BOD concentration, leaving reach I.
BODWST(I)	BOD concentration in waste for reach I.
C	constant, temperature equation.
CN	correction value, flow in upstream reach.
CNI	Intermediate variable.
CQREG(I)	corrected regulated flow, reach I.
D(I,J)	A state variable at stage I, state position J.
DEFIN(I)	DO deficit concentration, upstream end of reach I.
DEFOUT(I)	DO deficit concentration, leaving reach I.
DOS	Dissolved oxygen saturation concentration.
DOWST(I,J)	DO deficit concentration in waste load, reach I, month J.
DQ(I)	Amount of flow regulation reach I.
F(I,J,K)	The up-to-date total cost for k keeping at the present state from stage 1 stage I.
FL(I)	Length of reach I.

IWASTE(I)	Equals 1 for a waste load in reach I.
	Equals 0 for no waste load in reach I.
JR(I)	Downstream reach index.
NOR(I)	Number of reach I.
NR	Number of reaches.
NWASTE	Number of waste load stations.
NYR	Number of years.
PMW(I)	Peak waste load in reach I (used for periodic load function)
QG(I,J)	Weekly generated flow, station I, month J.
QNAT(I)	Natural (unregulated) flow, reach I.
QREG(I,J)	Regulated flow, reach I, month J.
QSUM	Sum of incoming flows, corrected-waste loaded reaches only.
QSUM2	Sum of incoming flows, total.
QWASTE(I,J)	Rate of waste discharge, reach I, month J.
R(I)	Random number, normal distribution, time frame I.
RCON(I)	Deoxygenenation error constant, reach I.
RLNTH(I)	Length of reach I.
RRN(I)	Temporary variable, random number generator, time frame I.
RRV	Intermediate variable.
RTEMP	Intermediate variable.
SDIF	Intermediate varaiable.
SIGMAT	Standard deviation, temperature data.
SPRD1	Summing variable - K1 computation.

SPRD2	Summing variable - BOD computation.
SPRD3	Summing variable - DO deficit computation.
T(L)	Temperature for reach L.
TCRIT	Critical time of flow, time to critical DO condition.
TIME	Time of flow in reach.
TMEAN	Mean temperature.
TT	Temperature at current time frame.
V(I,J,K)	A decision variable at state I. It represents the aeration capacity needed at point I-1 when the state variable at stage I-1 is D(I-1,J) and at stage I is D(I,K).
XK120(I)	Deoxygenation constant, reach I, at 20°C.
XK2	Reoxygenation constant.
XK220	Reoxygenation constant at 20°C.
XKK(I)	Dissolved oxygen concentration, violation condition.
XMINDO	Minimum dissolved oxygen concentration.

FIGURE A.3 RIPSIM - MAIN


START
MAKE DECLARATIONS, SET UP COMMON BLOCKS, INITIALIZE VARIABLES
READ CONTROL DATA: NUMBER OF STATIONS STATION NUMBERS FOR WHICH DATA ARE AVAILABLE, TEMPERATURE CONSTANT, SEED FOR RANDOM NUMBER SUBROUTINE.
A
SIMULATE STREAM FLOW, INITIAL AMOUNT OF WASTE AND DISSOLVED OXYGEN CONTENT IN RIVER SYSTEM ENTERING THE FIRST REACH. CALL SIM.
SUBROUTINE SIM.
READ WASTE PARAMETER VALUES, LENGTH OF REACH, SIMULATE RATE OF WASTE FLOW DISSOLVED OXYGEN CONTENT, BOD CONCENTRATION OF THE WASTE ENTERING THE REACH I. DO THIS FOR ALL REACHES. CALL OPTMOD.
B
SUBROUTINE OPTMOD.
SET UP ARRAYS TO STORE STATE VARIABLE VALUES FOR STATE J OF THE ITH STAGE, AND THE CORRESPONDING OBJECTIVE FUNCTION. DISCRETIZE THE STATE VARIABL INTO M VALUES (11).
1

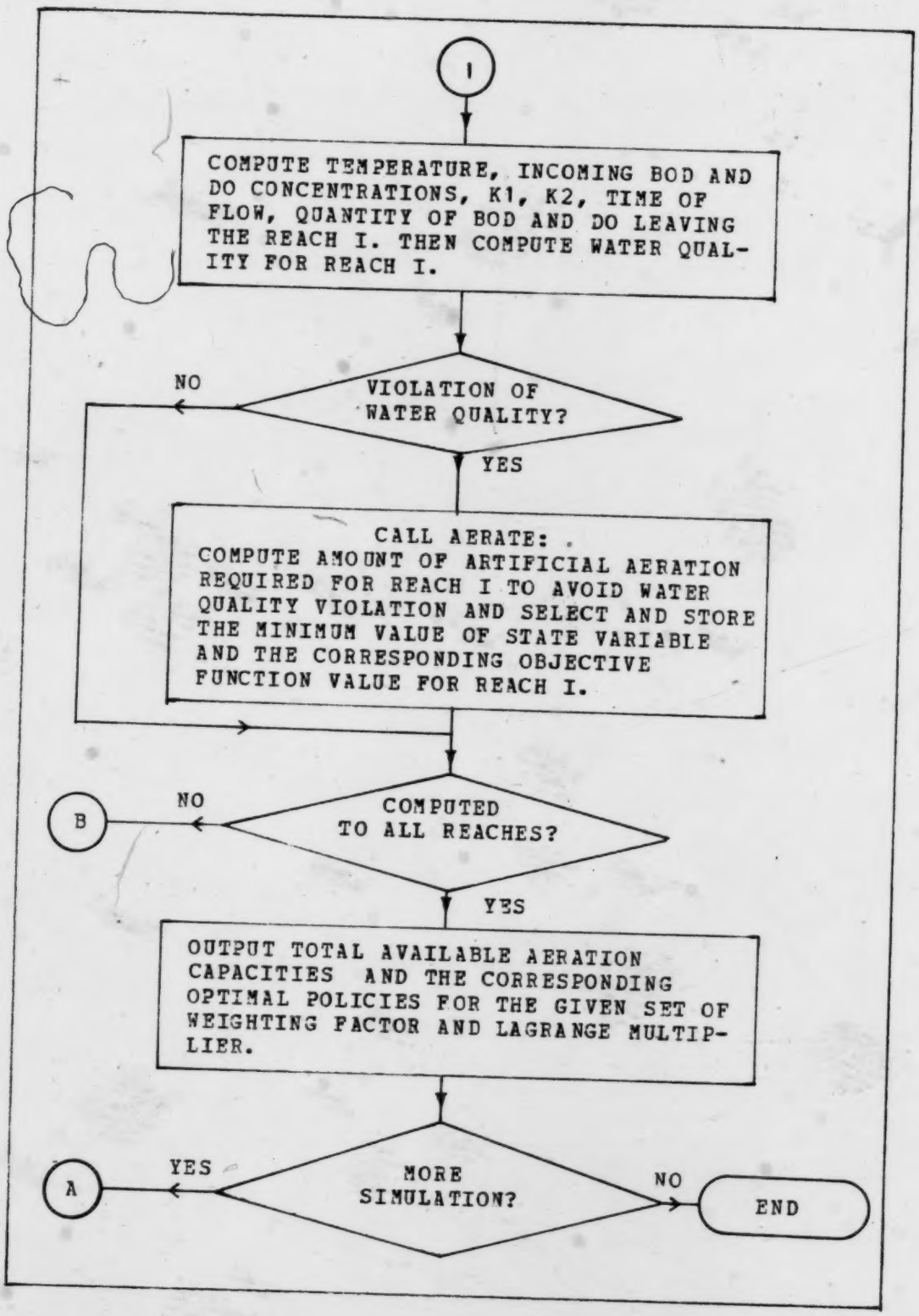
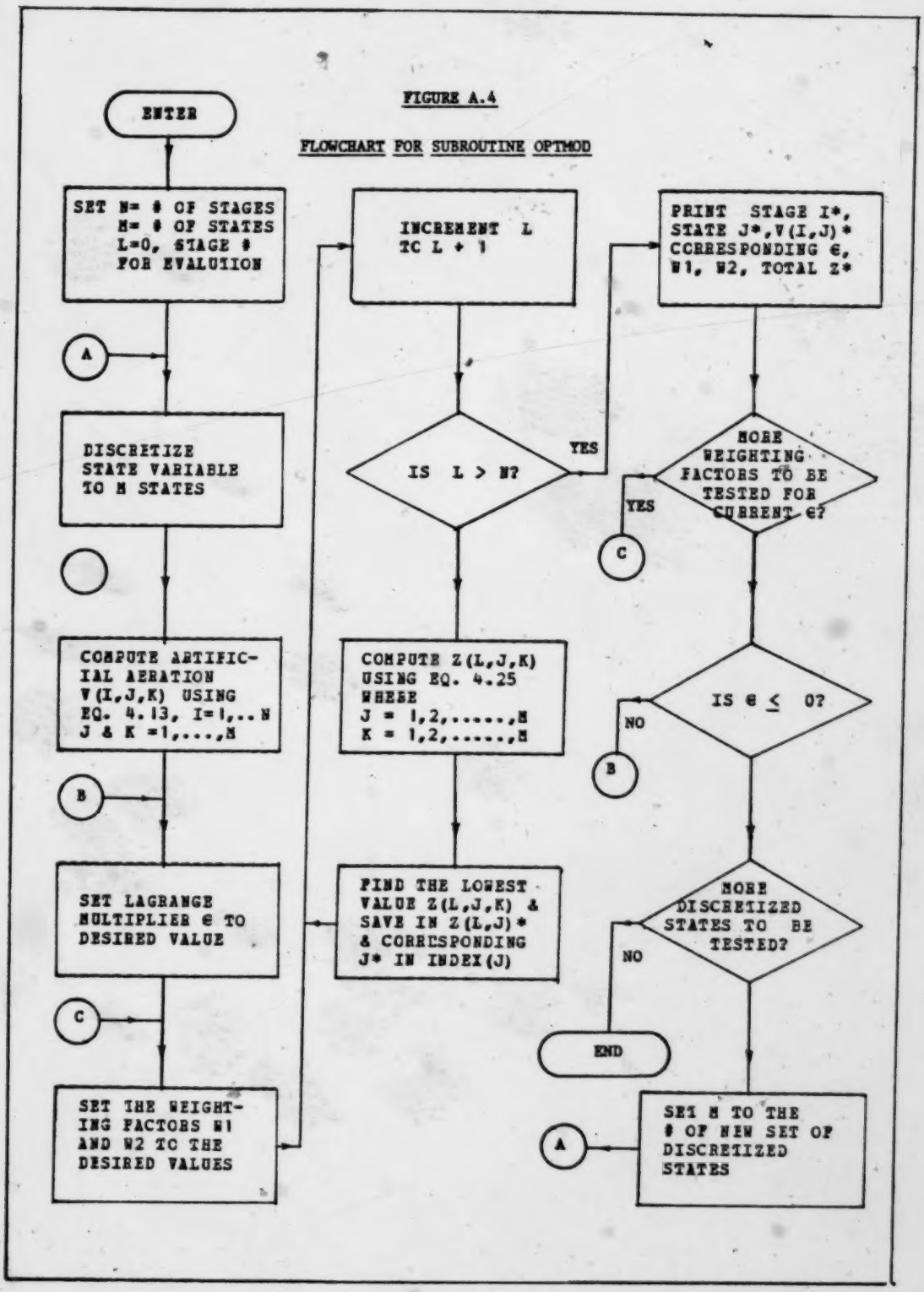

I
COMPUTE TEMPERATURE, INCOMING BOD AND DO CONCENTRATIONS, K1, K2, TIME OF FLOW, QUANTITY OF BOD AND DO LEAVING THE REACH I. THEN COMPUTE WATER QUALITY FOR REACH I.
VIOLATION OF WATER QUALITY?
NO
YES
CALL AERATE:
COMPUTE AMOUNT OF ARTIFICIAL AERATION REQUIRED FOR REACH I TO AVOID WATER QUALITY VIOLATION AND SELECT AND STORE THE MINIMUM VALUE OF STATE VARIABLE AND THE CORRESPONDING OBJECTIVE FUNCTION VALUE FOR REACH I.
B
NO
COMPUTED TO ALL REACHES?
YES
OUTPUT TOTAL AVAILABLE AERATION CAPACITIES AND THE CORRESPONDING OPTIMAL POLICIES FOR THE GIVEN SET OF WEIGHTING FACTOR AND LAGRANGE MULTIPLIER.
A
YES
MORE SIMULATION?
NO
END

FIGURE A.4

FLOWCHART FOR SUBROUTINE OPTMOD


ENTER
SET N= # OF STAGES
M= # OF STATES
L=0, STAGE # FOR EVALUTION
A
DISCRETIZE STATE VARIABLE TO M STATES
COMPUTE ARTIFICIAL AERATION V(I,J,K) USING EQ. 4.13, I=1,..N J & K =1,...,M
B
SET LAGRANGE MULTIPLIER ϵ TO DESIRED VALUE
C
SET THE WEIGHTING FACTORS W1 AND W2 TO THE DESIRED VALUES
INCREMENT L TO L + 1
IS L > N?
YES
COMPUTE Z(L,J,K) USING EQ. 4.25 WHERE J = 1,2,.....,M K = 1,2,.....,M
FIND THE LOWEST VALUE Z(L,J,K) & SAVE IN Z(L,J)* & CORRESPONDING J* IN INDEX(J)
PRINT STAGE I*, STATE J*, V(I,J)* CORRESPONDING ϵ, W1, W2, TOTAL Z*
MORE WEIGHTING FACTORS TO BE TESTED FOR CURRENT ϵ?
YES
C
IS ϵ ≤ 0?
NO
B
MORE DISCRETIZED STATES TO BE TESTED?
NO
END
A
SET M TO THE # OF NEW SET OF DISCRETIZED STATES

APPENDIX-B

THEORY OF OXYGEN SAG CURVE

One of the common and important indicators of water quality is Dissolved Oxygen (DO). The oxygen deficiency in a stream at any point is the resultant of two opposing processes, each governed by a different set of conditions - one consuming oxygen from the stream and the other replenishing the oxygen source, both processes proceeding as a time function (figure B.1).

The principal wastes which affect DO are those which are characterized by their Biochemical Oxygen Demand (BOD). BOD is generally defined as the amount of oxygen (DO) required by bacteria while stabilizing decomposable organic matter. The stabilization of waste matter using dissolved oxygen is called purification of water.

River pollution control requires careful consideration of the relationship between BOD and DO. One of the primary considerations in determinig the amount of waste (BOD) which can be released to a stream is the DO content of the stream at the point of discharge. Down stream from this point the DO content is reduced by the oxidation of organic material. At some point downstream the rate of oxygen recovery (reaeration) will exceed that of oxygen reduction

(depleation) and from that point onwards the DO content will gradually increase. The phenomena of depletion and recovery of oxygen level in a stream can be discovered by the Streeter-Phelps equations.

$$\frac{dD}{Dt} = k1L - k2D$$

This basic differential equation states that the net rate of charge in the DO deficit (dD/dt) is equal to the sum of (1) the rate of oxygen utilized by BOD in the absence of reaeration (K1L) and (2) the rate of oxygen absorption by reaeration in the absence of BOD (-K1D).

The critical oxygen deficit, Dc, is defined as the dissolved oxygen deficit at the time Tc, the oxygen content starts to increase, as shown in figure B.1. Frequently Dc is prescribed by regulatory agencies to be less than some maximum allowable level, Dl. If at any time the value of $Dc \leq Dl$, then the river is unpolluted. If $Dc > Dl$, then the river is polluted. To avoid this being happen, more air should be pumped into the river through aerators. This phenomena of artificially increasing the content of DO is called artificial aeration. How much air should be pumped into the the river system to avoid pollution is being the subject of this paper.

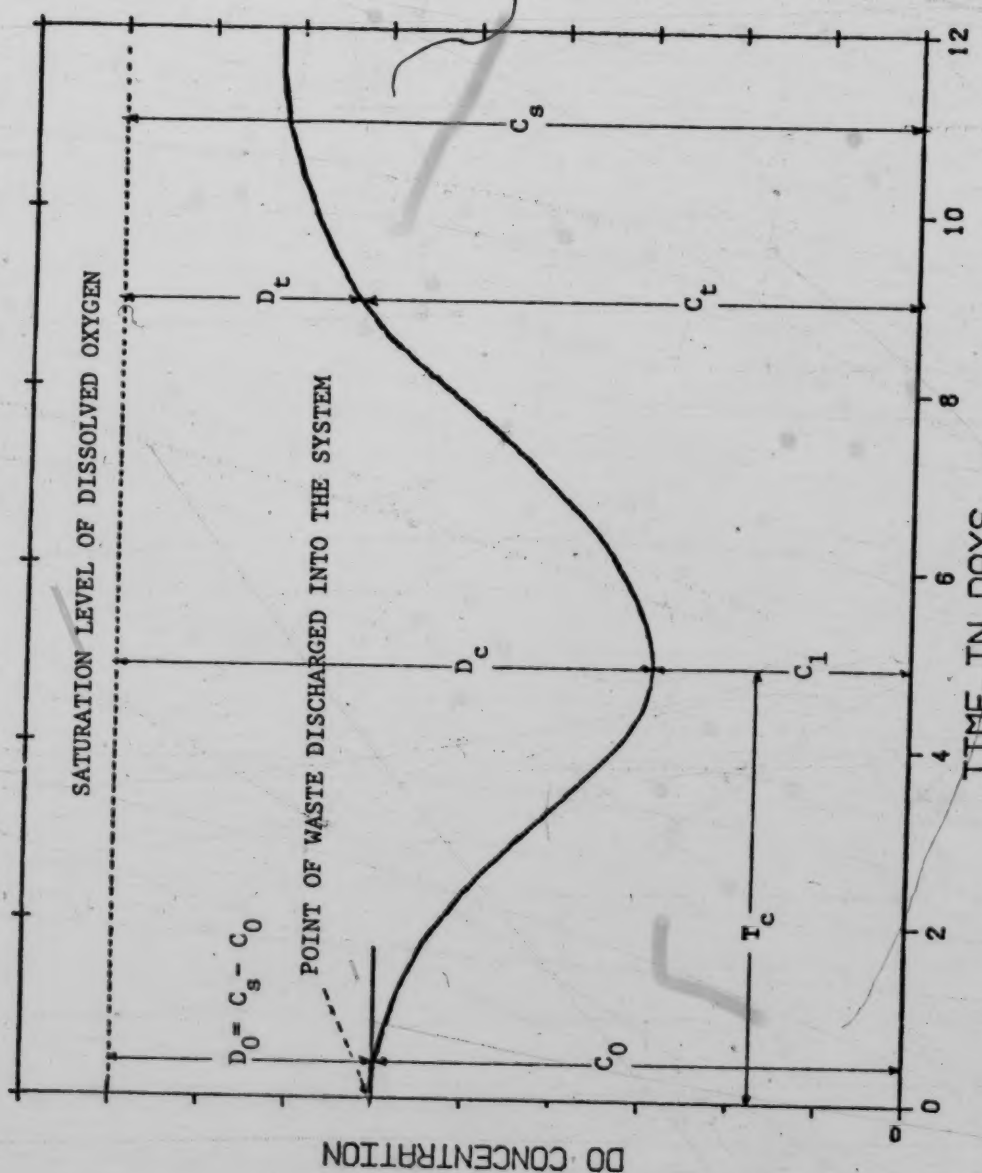


FIGURE B.1 DO SAG PROFILE

APPENDIX-C

NOTATIONS AND ABBREVIATIONS USED IN THIS THESIS.

A_i = Aerator located at the top of i^{th} reach.

BOD = Biochemical xygen Demend.

BOD_{in} = Quantity of waste already in the system which is input to the next reach.

BOD_{dis} = Quantity of waste discharged at the top of reach i.

Cfs = Cubic feet per second.

C_0 = Initial level of Dissolved Oxygen (DO) content at the top of a reach.

C_1 = minimum level of Dissolved Oxygen, specified by the stream standard law.

C_s = Saturation level of DO, a function of temperature.

C_t = level of Do at any point t days from the top of a reach.

D_c = Critical dissolved oxygen deficit.

DO = Dissolved oxygen content in water (mg/l).

D_0 = Initial Do deficit at the top of a reach = $(C_s - C_0)$

D_1 = Maximum DO deficit specified by the regulatory agency.

D_t = DO deficit at any point t days from the top of a reach $(C_s - C_t)$.

L_0 = initial BOD content at the top of a reach = $(BOD_{in} + BOD_{dis})$.

L_t = BOD content at any point t days from the top of a reach.

k_1 = Deoxygenation coefficient (rate of consumption of oxygen).

k_2 = Natural reaeration coefficient (rate of recovery of oxygen.

mg/l = miligrams per litre (unit of measurement).

N = Number of reaches (in this case N=24).

t = Distance from the top of a reach expressed in time units (days) = (distance/velocity).

V_i = Increment in the level of DO due to artificial aeration augmented at the top of a reach.

x_i = Length of reach i = $t_i - t_{i-1}$)

Z = The value of objactive function.

ϵ = Lagrange multiplier.